Irish Fisheries Investigations No. 27 2016

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Abstract

Eel Density Analysis (EDA) is a modelling framework that can be used to estimate eel populations in aquatic habitats. Survey data (primarily electrofishing operations) are used to build predictive models describing the presence/absence and the density of eel. These models are then applied to the entire network of aquatic habitat in the area of interest to estimate the total population size. The fluvial (riverine) population of yellow eel in Ireland was estimated using the EDA (v2.0) model (Jouanin et al., 2012). A total fluvial population of 8,032,834 yellow eels and 200,821 silver eels (using a silvering rate of 2.5%) was estimated for 2011. Eel presence and abundance decreased as the distance to the sea increased, and the percentage of calcareous geology in the catchments decreased. Stock indictors (B0, Bbest and Bcurrent) were calculated from these yellow eel estimates to enable the display of precautionary diagrams for each EMU in Ireland. Lake production was also calculated for 2011, using empirical data from a small number of catchments. A precautionary diagram for this total production (fluvial and lacustrine habitat) is presented, and compared with previous estimates of stock indicators for Ireland.

Keywords: yellow eel, silver eel, production model, density, escapement.

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Main report

Introduction

The European eel is widely distributed throughout over 90,000 km2 of inland, estuarine and coastal waters in Europe and parts of northern Africa (Moriarty and Dekker, 1997). Estimates of glass eel recruitment across Europe indicate that numbers fell in the 1980s to about 10% of former levels, and further to 1-5% since 2000 (ICES, 2008). This decline in recruitment was preceeded by a decline in landings two or more decades earlier (Dekker, 2003). There has been a slight increase reported for the last two years (2012 and 2013) (ICES, 2013) although the recruitment indices remain far below what can be considered healthy. The status of the stock has not changed in the last number of years, and remains critical (ICES, 2010). In 2007, the EU adopted the Eel Regulation (Council Regulation No 1100/2007), aimed at a recovery of the international stock. This required Member States to develop a three year Eel Management Plan for each EMU (Eel Managament Unit) by 2009, for the period 2009-2012. The second round of the EMPs runs for 2012-2015. The primary objective of these plans is to permit, with high probability, the escapement to the sea of at least 40% of the biomass of silver eel relative to the best estimate of escapement that would have existed if no anthropogenic influences had affected the stock. A crucial part of the EMPs therefore, is an estimation of silver eel production from each EMU. There is a variety of approaches available to assess silver eel production and escapement:

- technical measures that can be used to directly determine actual silver eel escapement by catching and/or counting silver eels
- proxy indicators based on knowledge of yellow eel populations model
- predictions and extrapolations.

The POSE project (Walker et al., 2011) describes the use of several methodologies for estimating silver eel production, using methods that are currently available within the European Eel scientific community. One of the methodologies, EDA (Eel Density Analysis vers 2.0: A statistic model to assess European eel (Anguilla anguilla) escapement in a river network) was applied to the Western EMU of Ireland during the course of the POSE project (Jouanin et al., 2012). Following the completion of the POSE project, it was felt that it would be worthwhile extending the use of EDA to all the EMU's of Ireland, and this document describes that process.

EDA is a framework of eel density analyses, which can be applied at River Basin District, Eel Management Unit or even national scales. It operates on a geolocalized river network database CCM v2.1 (Catchment Characterisation and Modelling), and relates yellow eel densities to environmental variables, including anthropogenic impacts, extrapolated from survey sites to the river basin.

The predicted yellow eel stock is converted to a potential silver eel escapement using a user-defined conversion rate. The model requires data on the presence/ absence and densities of yellow eel at sites throughout the river network, typically derived from scientific surveys (e.g. electro-fishing surveys). Additional data describing the distance of each site from sea and source, the temperature in each segment of the river network, the mean rainfall, the elevation, slope and stream order (Strahler and Shreve) are also desirable. The anthropogenic impacts are described as obstacle pressure (cumulative number of dams and their passability), land use and the presence of fisheries. EDA utilises the database PostgreSQL, combined with Quantum GIS and R. All of these software packages are open source.

The steps in applying EDA are:

1. Relate observed yellow eel presence/absence and densities to descriptor parameters by using a subset of national river segments where eel data are available
2. Extrapolate yellow eel density and presence/absence to each river segment in the country by applying the statistical model calibrated in step 1
3. Calculate the overall yellow eel stock abundance by multiplying these extrapolations by the surface area of each river segment
4. Estimate a potential silver eel escapement of each segment by converting yellow to silver eel abundance with a 2.5% silvering rate (R. Poole, pers. comm)
5. Calculate effective escapement by reducing potential escapement with mortalities during downstream migration
6. Sum the effective escapement from all the stretches to give estimates at EMU scale

EDA was developed and first applied in France, but has since been used in several countries to estimate silver eel production.

Methods

2.1 Principle of EDA

The principle of the model is to extrapolate yellow eel densities from surveys in each reach on a geo-localized river network. EDA first relates eel densities to explanatory variables, including anthropogenic impacts. The models describing these relationships (a presence/absence model and a density model) are then used to extrapolate eel desi-ties from survey sites to every river segment within an EMU. It calculates the overall yellow eel stock abundance, converts it to silver eel equivalents and estimates silver eel escapement by substracting silver eel mortalities due to anthropogenic factors. At this stage of development, EDA does not include a way of including lake population estimates (e.g. the results of fyke net surveys), and this is a major obstacle in using EDA to determine total silver eel production at an EMU level. We recognise this obstacle, and refer to it later in this report. As an interim measure, a number of catchments were identified where total silver eel production(i.e. river and lake production) was known. The fluvial estimate produced by EDA was subtracted from these total catchment production estimates, in order to quantify the lake production of silver eel. This lake production estimate was extrapolated to all lakes within each EMU and added to the fluvial production calculated by EDA to estimate total silver eel production per EMU. This exercise was only carried out for 2011, and is included here as a demonstration of how the inclusion of lake production estimates might impact on the stock indicators for Ireland.

2.1.1 Data requirements

EDA uses yellow eel survey data as the response variable in the modelling exercise. These survey data are generally multi-pass electrofishing surveys. In applying EDA to Ireland, survey data from several sources were collated (Table 2.1.1, Figure 2.1). These were extracted from the National Eel SQL database maintained by IFI. The CCM dataset (Vogt et al., 2007) was used as the GIS 'skeleton' on which to build the EDA model for Ireland. The CCM GIS layers cover the whole of Europe, and include catch-ment boundaries (or seaoutlets), river segments and lakes. The CCM river segments are the segments refered to in the rest of this document (Figure 2.2). Various data sources were then used to build a suite of explanatory variables that were thought to explain densities of yellow eel in freshwaters (Table 2.1, Figure 2.3-Figure 2.6). Temperature (C) and rainfall (mm) statistics were extracted from the CCM dataset (Vogt et al., 2007), corresponding to the long-term average annual temperature and precipitation in the primary catchment.

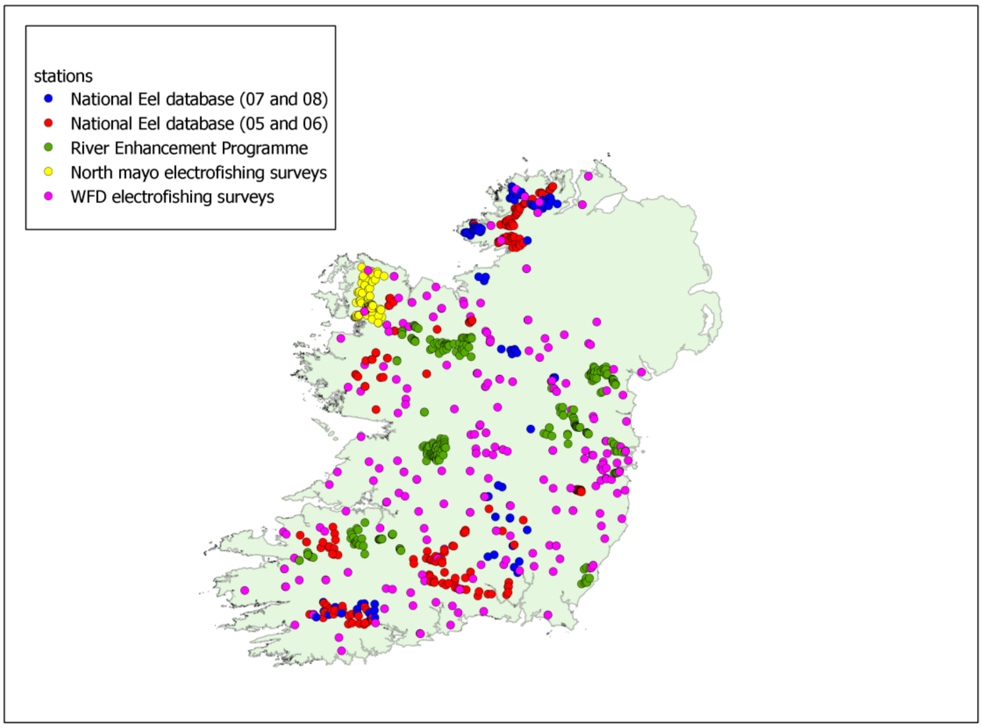


Figure 2.1: Location of electrofishing surveys in Ireland from which eel catches were extracted.

Table 2.1: Data sources used in the application of EDA (vers. 2) to Ireland.

Data	Details	source
Eel	Environmental River enhancement programme (enhancing drained rivers)	IFI
	Data extracted from the National Eel database 2005-2008	IFI(various sources)
	WFD directive fishing 2008, 2009, 2010, 2011	IFI
	Mayo electrofishing surveys (MI and IFI) 2007-2010	MI/IFI
River	CCM v2.1: Catchment Characterisation and Modelling, a European hydrographical databases	CCM v2.1 (Vogt et al., 2007)
	Hydromorphometry	
	distances to the sea	CCM v2.1
	distance to the source	CCM v2.1
	relative distance (between sea limit and upstream source)	CCM v2.1
	elevation	CCM v2.1
	slope	CCM v2.1
	stream order	CCM v2.1
	Shreve index	CCM v2.1
	Strahler index	CCM v2.1
	Meteorology	
	temperature	CCM v2.1
	rainfall	CCM v2.1
	Geology	
	precentage calcareous geology	Compass Informatics
Impacts	Dams	Salmon Barriers 2003
	Land cover	Corine land cover 2006 (CLC2006) 250 m - version 12/2009. EEA https://open-data.europa.eu/en/data/publisher/eea
Silvering rate	R. Poole (pers. comm.)	Burrishoole mark-recapture

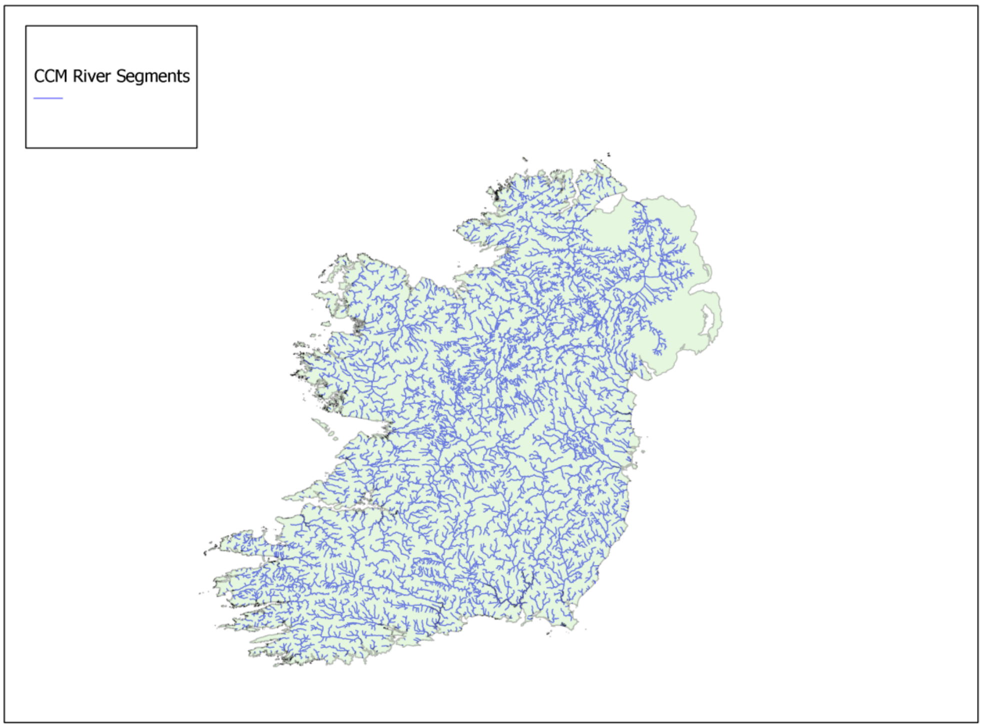


Figure 2.2: The river segment baseline for Ireland, derived from the European CCM dataset.

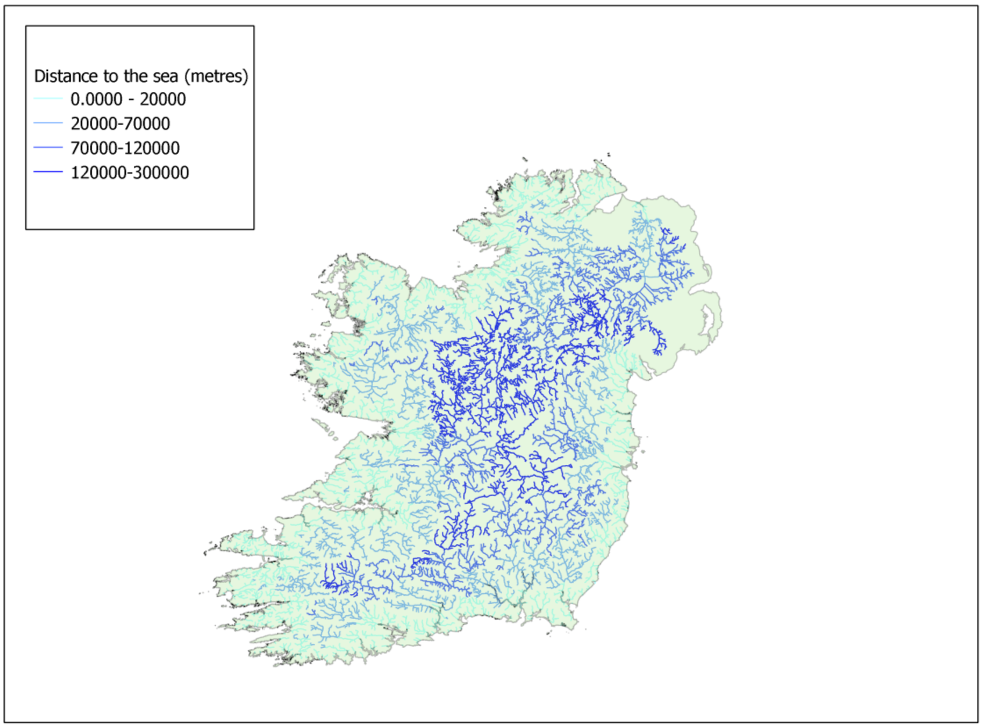


Figure 2.3: River segments classified according to the distance to the sea of each segment.

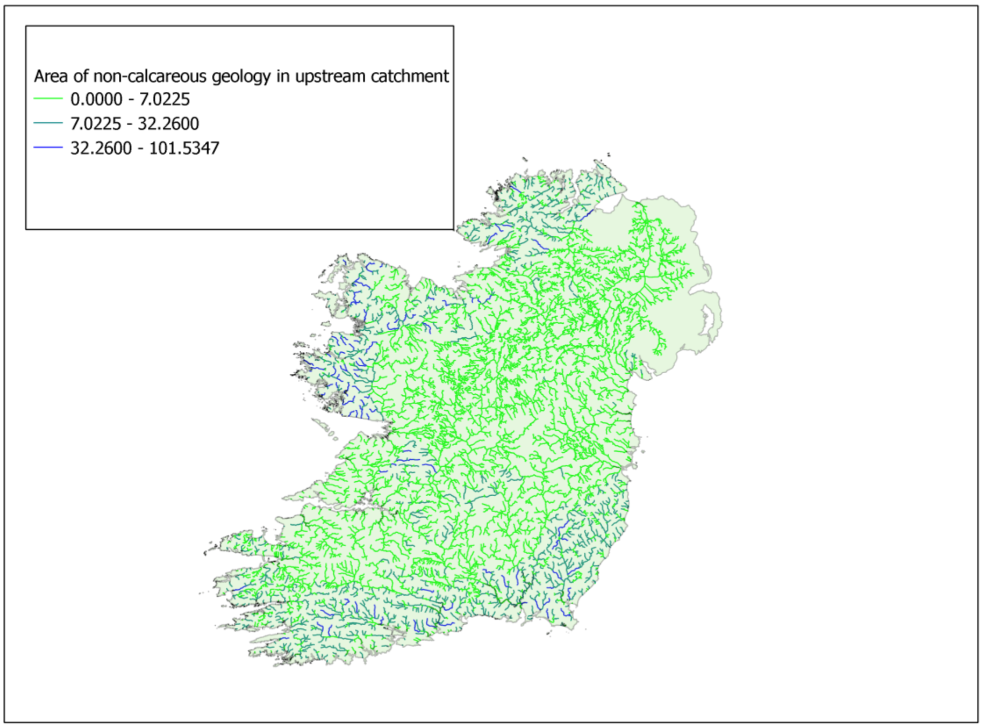


Figure 2.4: River segments classified according to the amount of non-calcareous geology in the upstream catchment.

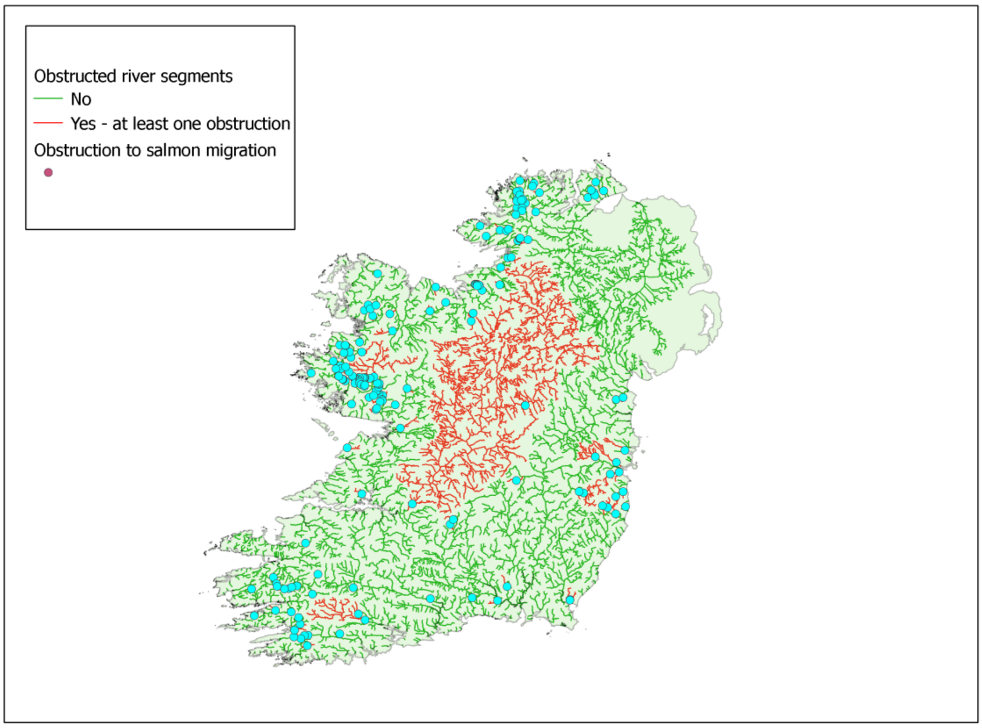


Figure 2.5: River segments classified according to whether there is a known obstruction to fish migration.

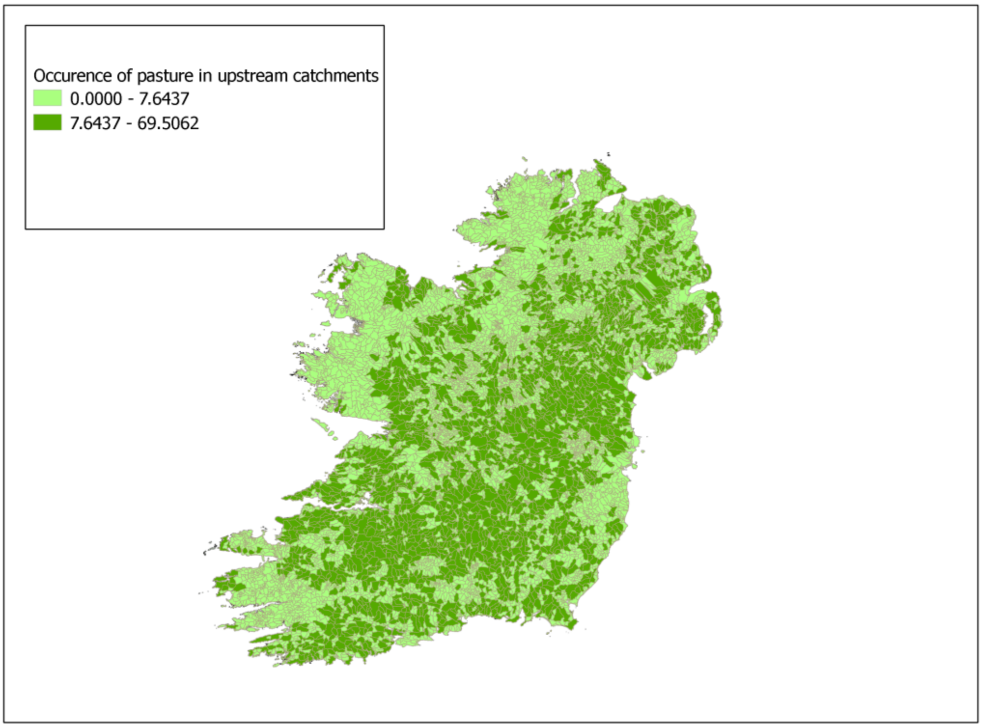


Figure 2.6: Occurrence of pasture in upstream catchments. Landuse data were extracted from Corine Land Cover (2006) and joined to river segments described in the CCM (vers 2.1) GIS layers. .

2.1.2 Biological data

Electrofishing operations corresponding to catches made in either one or two electrofishing passes were selected for the model. The first two passes were used to calculate the relation between the number at the first pass (N_{p1}) and the total Carle and Strub (Carle and Strub, 1978) estimate (N_{CS}). The effciency of the catch in the first pass was calculated as :

$$\bar{e} = \overline{\left(\frac{N_{p1}}{N_{CS}}\right)}$$

For operations with only one pass, the density was estimated as:

$$N_{CS} = \frac{N_{p1}}{\bar{e}}$$

The density d was finally calculated as :

$$d = \frac{N_{CS} * 100}{S}$$

where S is the wetted surface of the electrofishing operation in m^2 and d is expressed as the number of eel per 100 m^2. EDA also requires some biological variables specific to each EMU to calculate different potential escapements, The parameters used in the extrapolation model are the average duration of eel life, the average weight of glass eel, yellow eel and silver eel. An estimation of the natural mortality is also required.

Finally an estimation of anthropogenic impacts in the basin is necessary to calculate stock indicators and escapement. The model requires a time series of the landings of yellow eel and silver eel

2.1.3 River topology

The model is based on a geo-localized river network called CCM v2.1 (Catchment Characterization and Modelling) (Vogt et al., 2007). The river segments used in the subsample from Ireland have an average length of 2.73 km and range from 0.1 to 25.7 km.

The CCM2.1 database includes a hierarchical set of river segments and catchments based on strahler order. The primary catchment unit is the drainage area, the smallest entity drained by the CCM river stretch. The system allows identification of all up-stream catchments and all river segments downstream of a given point along the river network. All the river segments are connected.

2.1.3.1 Fishing

Landings of yellow eel and silver eel between 2001 amd 2008 were taken from the National Report for Ireland on Eel Stock Recovery Plan (Anon., 2008) and the Report on the status of the eel stock in Ireland 2009-2011 (Anon., 2012). These landing data were used to account for Fishing mortality in the years preceeding the closure of the eel fishery in Ireland in 2009.

2.1.4 Supplementary variables calculated

2.1.4.1 Segment characteristics

All variables are calculated at the segment level. The following variables were calculated from the river topology of the CCM.

- The distance from the sea (km) was calculated as the distance from the river mouth to the downstream node of the river segment, plus half of the length of the river segment.
- The distance from the source (km) was calculated as the distance from the upper node of the river segment to the farthest source of the upstream basin, plus half of the length of the river segment.
- The relative distance (km) was calculated as the distance from the sea / total distance (distance to sea + distance to source).
- The Strahler and Shreve stream order correspond to calculations of the rank of the river, according to the number and the order of tributaries.
- The mean elevation (m) is the average elevation in the primary catchment.
- The mean slope (degrees) is the average slope in the primary catchment.
- The altitudinal gradient (%) is the gradient calculated as [(elevation at the up-stream node - elevation downstream node)/ segment length)*100)].
- The area of drainage of the primary catchment.
- The area of drainage upstream for the river segment (km^2).

2.1.4.2 River width

Predicted river widths for every river reach in Ireland are available in McGinnity et al. (2012), where upstream catchment area and Shreve index were used as predictors of river with. However, these could not be applied to the river segments described in the CCM as the spatial coverage of rivers and lakes in the CCM dataset are different to that used in McGinnity et al. (2012), which was based on Irish Ordnance Survey coverages. River width here was instead modelled using the calibration data set described in McGinnity et al. (2012) but using river segment data extracted from the CCM.

2.2 Modelling

Two datasets were prepared for the eel modelling exercise:

- A dataset named CCM which stored information about the CCM2.1 and all the supplementary explanatory variables.
- A dataset named ERS (Electrofished river segments) which contains information about electrofishing operations, one line per river segment. Some river segments may be repeated when multiple electrofishing operations took place at the same site.

Both datasets are based on the primary catchment unit, the drainage area. Dams and electrofishing information were attributed to the nearest river segment at a distance of 300 m. Some data were not included as they were located on tributaries which were not included in the CCM2.1 coverage. The ERS dataset is limited to segments where electrofishing took place while the CCM contains all river segments in Ireland. The ERS dataset was used to build models and as a second step the CCM dataset to extrapolate yellow eel densities.

2.2.1 Analysis of explanatory variables

Variables were checked for representativity before being included in the model. This was done by testing the homogeneity of distributions between the ERS and the CCM using a chi sq test. The data were split into comparable sized groups.

As a second step, homogeneous variables were selected and the ERS dataset was ex-plored to test for collinearity between exploratory variables. For this, a hierarchical clustering analysis was used, on Spearman's rank correlation ρ between pairs of variables. This method allowed to test the effect of all variables without putting correlated variables together in the same model. Pairs of variables with $\rho > 0.4$ were not used together in the same model.

2.2.2 Model selection

The yellow eel density (d) was fitted against the year and other environnmental variables with a Generalized Additive Model (GAM) (Hastie and Tibshirani, 1990). This procedure involved a two step modelling approach:

- The presence-absence model (Δ) used a binomial distribution with a logit family link to calculate the probability of fish presence. This model was calibrated using every eel survey in the dataset, with the aim of predicting where eels are likely to be present or absent.
- Then for positive densities, a Gamma (Γ) model with a log link was used to model the density (in terms of number) of eel, where they are found to be present.

The multiplication of two models ($\Delta\Gamma$) allows the prediction of eel densities. The use of a ($\Delta\Gamma$) approach was rendered necessary by the log-normal distribution of density data - which necessitates a log transformation, or a GLM with a gamma distribution and a log link - and the large number of zeros in the dataset -those are incompatible with a log transformation. The combination of the two models ($\Delta\Gamma$) was used to estimate eel densities for all the segments in the CCM. Variables for GAMs were computed with a cubic spline smoother for each temporal and environmental variable (Wood, 2000). The level of the smoother was selected as lower than 4 for environmental variables to reduce the risk of overfitting. The smoother for the year was selected according to goodness of fit (package mgcv in R statistical software), in order to allow for a possibly large temporal variation.

The best density model was selected by the Akaike's Infor-mation Criterion (AIC), with the lowest Akaike Information Criterion indicating the best fit (Akaike, 1973). The Cohen's κ (kappa) coefficient was used to determine the best fit presence-absence model. (Cohen, 1968; Manel et al., 2001). Model fits with Kappa values lower than 0.2 are considerd 'fair', with values of 0.4 − 0.6 as 'moderate', 0.6 − 0.8 as good and 0.8 − 1 'very good'. The probability threshold used to predict occurence tends to be correlated with Kappa.

2.3 Stock and escapement

2.3.1 Fluvial production predicted by EDA

The yellow eel abundance (*Nyccm*) was calculated for each river segment (*r*) from the width of the river and the surface calculated in 2.1.4.2. as :

$$
\begin{aligned}
Nyccm_r &= \widehat{\Delta_r}\widehat{\Gamma_r}\widehat{W_r}L_r \\
&= \widehat{\Delta_r}\widehat{\Gamma_r}\widehat{S_r}
\end{aligned}
$$

Where $\widehat{\Delta}_r$, $\widehat{\Gamma}_r$ and $\widehat{W}_r$ are the predictions for the delta, gamma, and river width models respectively, L_r is the river segment length and S_r is the segment area. The area of fluvial habitat quantified using the Irish Ordnance Survey contained in the National Eel Managament Plan (Anon., 2008) is quite different from that predicted using the CCM data coverage (Table 2.2). The ratio between the two was used to correct the fluvial habitat areas for each EMU, in order to give a more realistic biomass of eel per hectare. There are two main reasons why this correction is needed. Firstly, the CCM dataset does not include any first order streams, which can often constitute important Eel habitat. Secondly, river segments in the CCM dataset include segments running through the middle of lakes, which the OS quantification does not. This explains the very large discrepancy between the two estimates for the Shannon EMU (the CCM estimate is three times larger than the OS estimate), as the CCM estimate includes main river segments, with a wide predicted width running through the likes of Lough Derg and Lough Ree. By using the ψ ratio in Table 2.2, the CCM dataset is corrected for these two discrepancies. This correction was carried out before the escapement for each EMU was calculated. The number of eels in each EMU was estimated by summing the total number of eels predicted for every river segment ($Nyccm_r$) in an EMU and converting this to the number of eels for the EMU, as represented by the OS coverage (*Nyos*) using the ψ coefficient calculated at the EMU (*e*) level:

$$
Nyos_{r,e} = \frac{Nyccm_{r,e}}{\psi_e}
$$

Table 2.2: Fluvial habitat areas predicted for the CCM river segments or measured off OS maps, and the ratio (ψ)between the two

EMU	$\sum \widehat{Sccm}(1)$	$\sum \widehat{Sos}(2)$	ψ (1/2)
NorW	42.15	38.34	1.10
West	37.39	33.42	1.12
Shan	153.61	50.76	3.03
SouW	29.32	31.32	0.94
SouE	30.04	40.38	0.74
East	25.18	21.82	1.15

Stock indicators were then derived from the silver eel escapement as following;

- The potential escapement $B_{potential}$ (in biomass) of each EMU correspond to the sum of the number of silver eel produced in each segment (*r*). This $B_{potential}$ is the stock of silver eels before downstream migration.
- The current escapement $B_{current}$ (in biomass) is the potential escapement reduced by anthropogenic mortalities (silver eel fisheries and turbines mortality) during the downstream migration.

$$\begin{aligned} Bcur_{e,f} &= Bpot_{e,f} - Btu_{e,f} - Bs_{e,f} \\ &= \sum_{r \in e} (Nyos_r) w_e tau_e - Btu_{e,f} - Bs_{e,f} \end{aligned}$$

where :
Bpot= Biomass of silver eel estimated at the segment level by EDA,
Btu=Biomass of silver eel killed by turbines,
Bs=Biomass of silver eel caught in fishery,
Nyos=Number estimated on the CCM and corrected to correspond to OS river surface,
w= mean weight of a silver eel,
tau=annual proportion of the yellow number that becomes silver and migrate to the ocean,
e= EMU,
f = fluvial part of the catchment,
r= riversegment.

The numbers of eels transported around the dams were removed from the calcu-lation of *Btu* using:

$$\begin{aligned} Btu_{e,f} &= \sum_d (Bup_d - Btra_d \rho_d) \tau_d \\ &= \sum_d \left(\sum_{r \in r_{up}(d)} (Nyos_r w_e tau_e) - Btra_d \rho_d \right) \tau_d \end{aligned}$$

And the same is done to calculate the fraction of silver eel catch coming from the rivers

$$Bs_{e,f} = Bs_e * \rho_e$$

where :

d a hydropower dam,
r a river segment,
$r_{up}(d)$ river segment located upstream from dam d,
Btu_d =Biomass of silver eel killed hydropower dam d,
Bup_d =Biomass of silver eel estimated upstream from the dam (lakes are not included),
$Btra_d$ =Biomass of silver eel transported around that dam,
ρ_e= proportion of fluvial (versus lake) area in the EMU,
τ_d =turbine mortality estimated at dam d

- The best escapement B_{best} is the biomass of silver eels which would escape with-out anthropogenic pressure.
- The pristine condition escapement Bpristine or B_0 was extracted from the ICES WKEPEMP report on compliance with eel managements plans across Europe (ICES, 2013).

The 4Bs are expressed annually in kg per year.

2.3.2 Inclusion of lake production

While EDA produces a prediction of the number of yellow eels in the fluvial habitat of the country, it does not include any estimate of lake production. As lakes probably produce the majority of silver eel in certain Irish EMU's, we felt it necessary to include some estimate of lake production at this stage. To calculate lake production per hectare of lake surface area, catchments where total production of silver eel have previously been estimated were identified. These catchments were Burrishoole, Shannon, Erne and Corrib. Silver eel production was estimated for these catchments using total traps (Burrishoole) or by extraploting from commercial or scientific fisheries (Anon., 2012). The EDA prediction of number of silver eels being produced from the fluvial areas of the catchment (converted to silver eel using a silvering rate of 2.5%) were subtracted from the total production to give an estimate of how many eels were being produced in the lake habitat. This estimate was averaged for the period 2009-2011 and divided by the lake habitat area to give silver eel production in number of eel per hectare for each of these catchments. Where applicable, these values were used at the EMU level (i.e. when one of the catchments was within that EMU). An average of all the estimates was used in EMU's which did not contain one of these index catchments. The combination of EDA's prediction of river production with this estimate of lake production was used to calculate stock indicators for 2011. A time series of total production including lake production was not possible as there were not enough lake data to warrant this calculation. The current biomass in this calculation is thus calculated from the production of the lakes in the EMU (P_e) and the lake surfaces (Sl_e). In these calculations, the biomass of silver eel landings and turbine mortality are no longer weighted by the ratio between river and lakes surfaces areas.

$$Bcur_e = Bpot_e + P_eSl_e - Btu_e - Bs_e$$

$$Btu_e = \sum_d (Bup_d + P_eSl_d - Btra_d)\,\tau_d$$

2.4 Organisation of the work

All data were processed with SQL queries using postgreSQL 9.1 and all calculations for variables, models and predictions were carried out using R statistical software (version 3.0.2)(R Core Team, 2013). The algorithm and scripts are grouped on a "http://trac.eptb-vilaine.fr:8066/EDA". A guest access can be provided to interested collaborators. The software Eclipse and subversion were used for a collaborative work and code maintenance.

Results

3.1 Electrofishing data

All electrofishing operations were extracted from the database developed and populated during the POSE project (Walker et al., 2011). From an initial number of 914 electrofishing sites, 903 were projected at less than 500m from a CCM river segment. These resulted in 1,755 electrofishing surveys (operations). The number of surveys with two passages allowing for a Carle and Strub (1978) estimate was 1,342 and these were used to calculate the average efficiency of a single pass electrofishing (0.44) and extrapolate the number of eels from an additional 411 surveys. The total number of surveys where density could be calculated was 1753. This was reduced to 1657 surveys as in some cases, the wetted area of the station was not reported. The final number of surveys used to calibrate the model was 1,634 from 914 stations, during 10 years between 1991 and 2011 (Figure 3.1).

The number of electrofishing surveys available for analysis was low prior to 2002, and biased towards sites in certain parts of Ireland, so the modelling exercise was re-stricted to surveys conducted from 2002 onwards (Figure 3.2). Electrofishing stations were generally well distributed amoung the river segments of Ireland. There was no apparent bias in distributions between the ERS river segments and those of the entire country, as captured in the CCM river segments. This provides confidence that the river segments from where eel data are available provide a good representation of the river segments throughout the country (Figure 3.3).

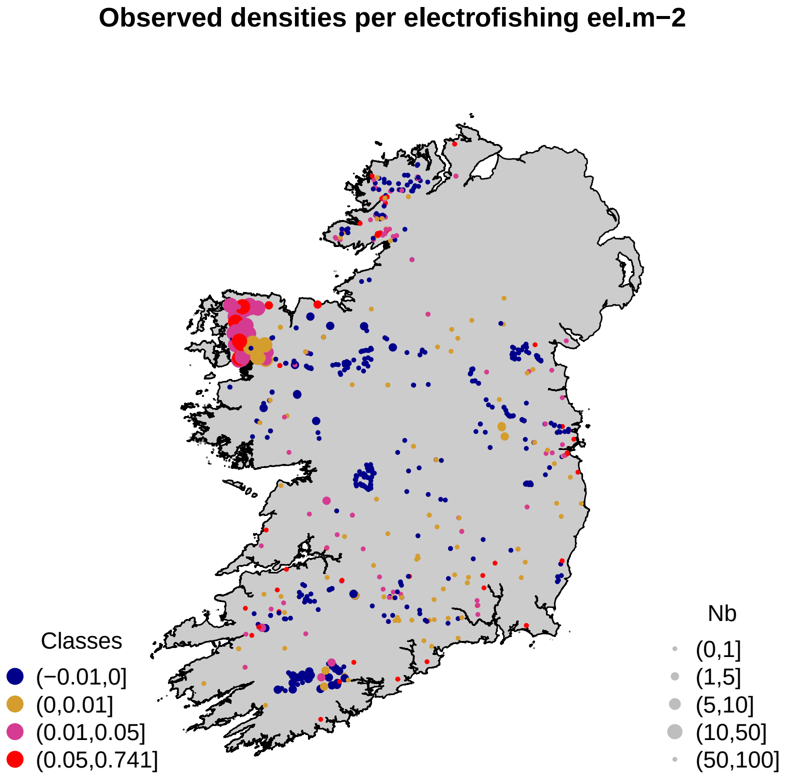


Figure 3.1: Average densities (eel.m²) observed for electrofishing survey stations in Ireland. Nb gives the number of surveys carried out at each station.

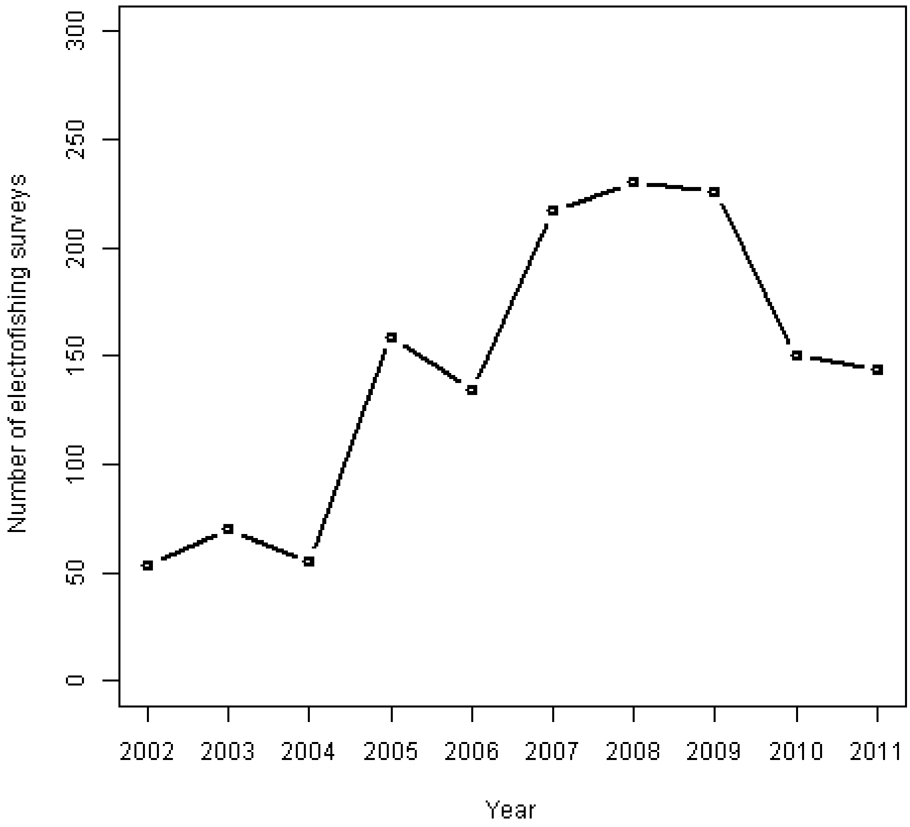


Figure 3.2: Number of electrofishing surveys per year included in this analysis

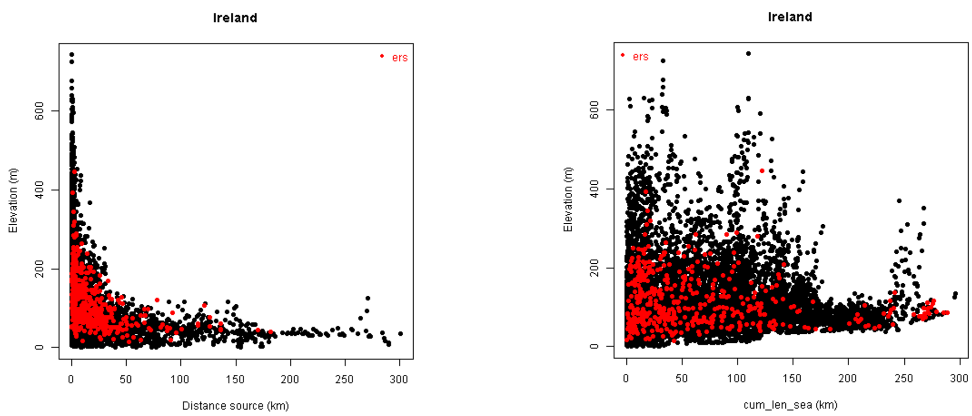


Figure 3.3: Representation of electrofishing sites (red) in the Irish basins in the CCM river network (black) depending on elevation and distance from the sea or from the source.

3.2 Selection of explanatory variables

The homogeneity tests between the ERS and CCM datasets indicated that the distribution of explanatory variables were homogeneous for all variables (Annexe II), with (χ^2>0.05) in all cases. This indicates that the ERS segments are likely to give a fair representation of the types of river segments inhabited by eel.

Pairwise tests between explanatory variables indicate some degree of correlation between certain variables (e.g. percentage of agricultural land is unsurpisingly strongly negatively correlated with the percentage of unimproved pasture) (Figure 3.4, 3.5 and 3.6). The aim of these correlations tests, in combination with the hierarchical clustering of potential variables below, is to indicate which pairs of variables should not be considered in the same model, and thus avoid collinearity problems. For example, variables that group together in the cluster analysis (Figure3.6) such as the Strahler, Shreve and Schneider indices should not be added to any model at the same time.

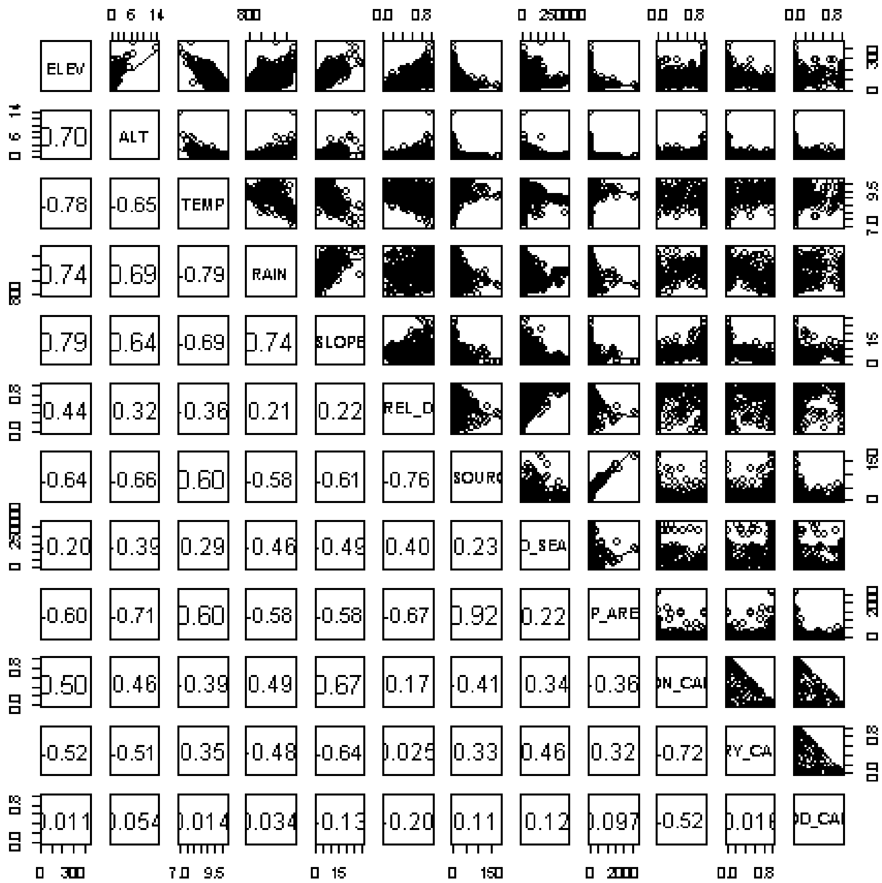


Figure 3.4: Pairwise correlations based on the Spearman rank correlation coefficient (ρ) between pairs of explanatory variables that may explain eel densities.

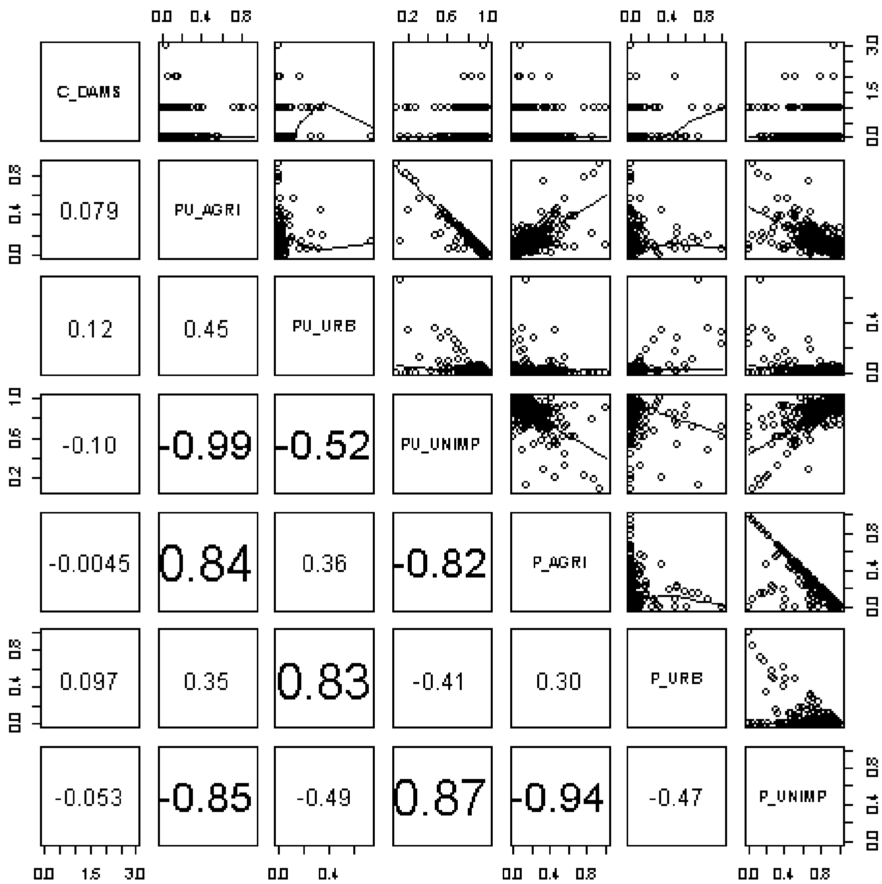


Figure 3.5: Pairwise correlations based on the Spearman rank correlation coefficient (ρ) between pairs of explanatory varibles that may impact eel densities.

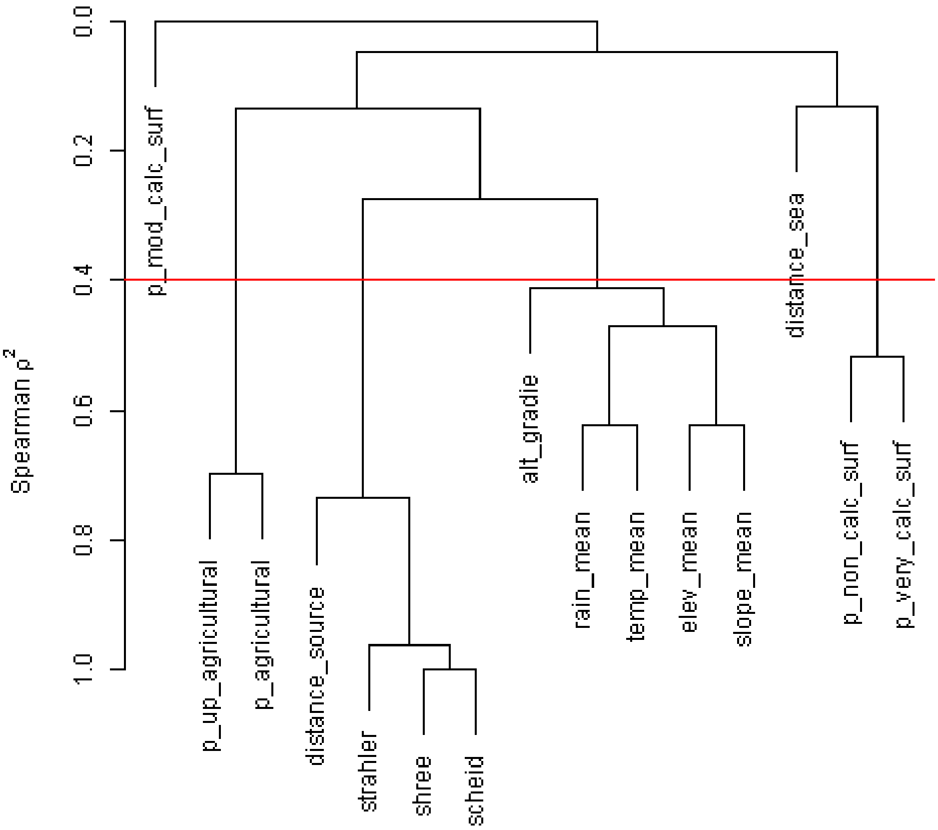


Figure 3.6: Dendogram by hierarchical clustering of the potential explanatory variables with Spearman's rank correlation as the similarity measure. The dendrogram is cut by a vertical line at Spearman ρ=0.4. Variables selected within a group, to the bottom of the dendogram, were entered separately in the eel models.

3.3 Models

3.3.1 River width model

The best model of river width included EMU as a random variable, along with upstream catchment area and the percentage of very calcareous geology in the catchment (Equation 3.1, Adjusted R^2=0.54, Table 3.1, Figure 3.7).

$$\begin{aligned} &log(r) \approx f(up\ catchment\ area) + f(geol) + \alpha emu + \delta + \epsilon_{emu} \\ &\epsilon_{emu} \sim N(0, \sigma_d^2)\ d = 1, ..., 6 \end{aligned} \tag{3.1}$$

where *log*(*r*) = natural log transformed river width, *emu*= EMU, *geol*= geology, percentage of highly calcareous surface, *α* coefficients for the model, *f* cubic regression splines with 3 degrees of freedom, *delta* intercept, ϵ_{emu} residuals. This model was applied to each river segment in both the ERS and the CCM datasets to predict a segment width, and hence a segment area for all Irish rivers.

Table 3.1: Details of the model 3.1used to predict river width for each river segment

	Dependent variable:
	d != 0
Intercept	2.278 (0.098)***
NorW	0.345 (0.108)**
Shan	0.777 (0.178)***
SouE	−0.308 (0.119)*
SouW	1.00 (0.119)
West	0.056 (0.134)
	estimated degrees of freedom
s(distance_source)	3.867***
s(p_very_calc_surf)	1.000***
Observations	245
Adjusted R^2	0.541
Note:	*p<0.1; **p<0.05; ***p<0.01

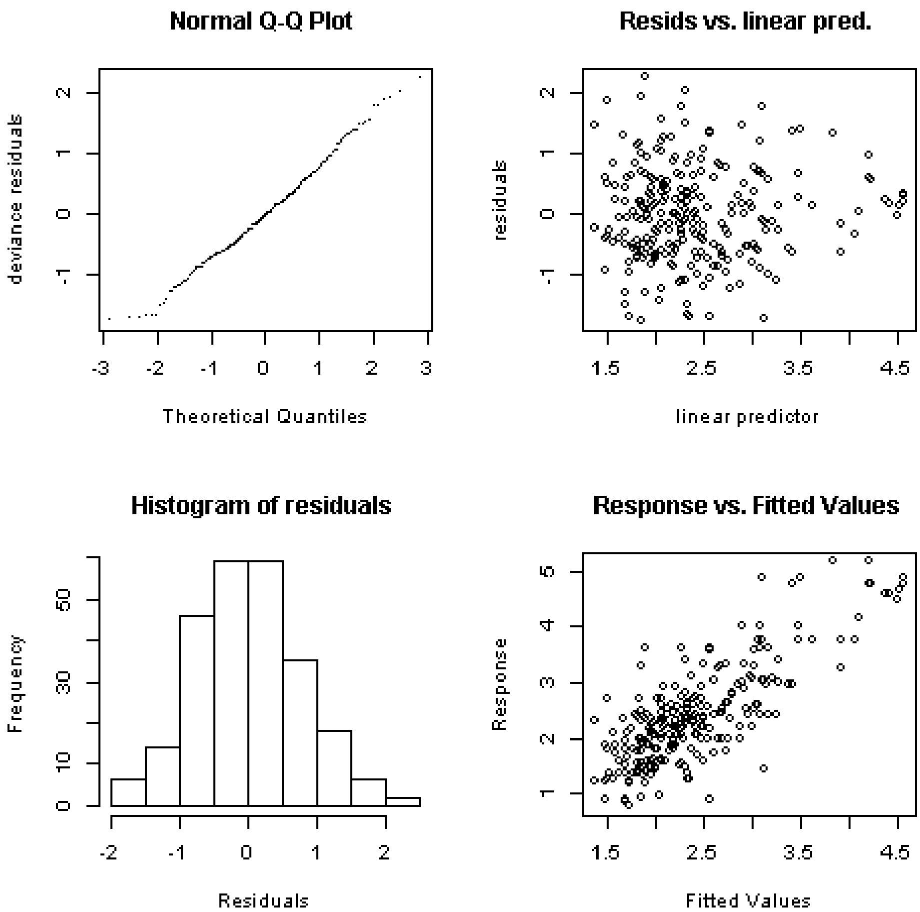


Figure 3.7: Plot showing the validation of the riverwidth (Formula 3.1) model.

3.3.2 Survey data model

For each model (presence-absence Δ and density Γ), 3600 models were tested in an analysis with an R function which tested in turn every combination between groups of uncorrelated variables. The 10 Δ and Γ models with the best AIC were selected at the end of the procedure. Variables with low levels of significance and probable spurious effects were then removed from the model. The degrees of freedom of the smoother were also adapted after a graphical examination of the variable responses.

3.3.2.1 Presence absence - Δ model

The model was calibrated with the results of 1438 electrofishing operations. The best presence-absence model was:

$$Density \sim year + month + p\ non\ calc\ surf + s(log(distance\ to\ sea\ by\ EMU, 4)$$

For a threshold selected at 0.4 (Max Kappa), the Kappa was 0.273 which indicates a good fit, while the percentage of deviance explained was 14% (Table 3.2). The model correctly predicts 67% of observed data, 34% of eel absence data, 92% of eel presence data. The partial residuals of the model shows the effect each variable has on the model results (Figure 3.8 and 3.9). For example, the probablility of finding eels decreases in catchments with more acid geologies (i.e. a high percentage of non-calcareous geology). The model also predicts that as the distance from the sea increases, the probability of finding eels decreases until the sea is approximately 150km away (Figure 3.9). After 150km, the model breaks down somewhat, as evidenced by the larger confidence intervals. This is a reflection of the fact that the Shannon is the only EMU with a significant proportion of river segments greater than 150 - 200 km from the sea. Some large residuals for the presence-absence models occur in the upper Shannon basin, indicating that the model predictions of presence are too low. (Figure 3.10). This may be a reflection of the fact that eel are transported around Ardnacrusha (Figure 3.9).

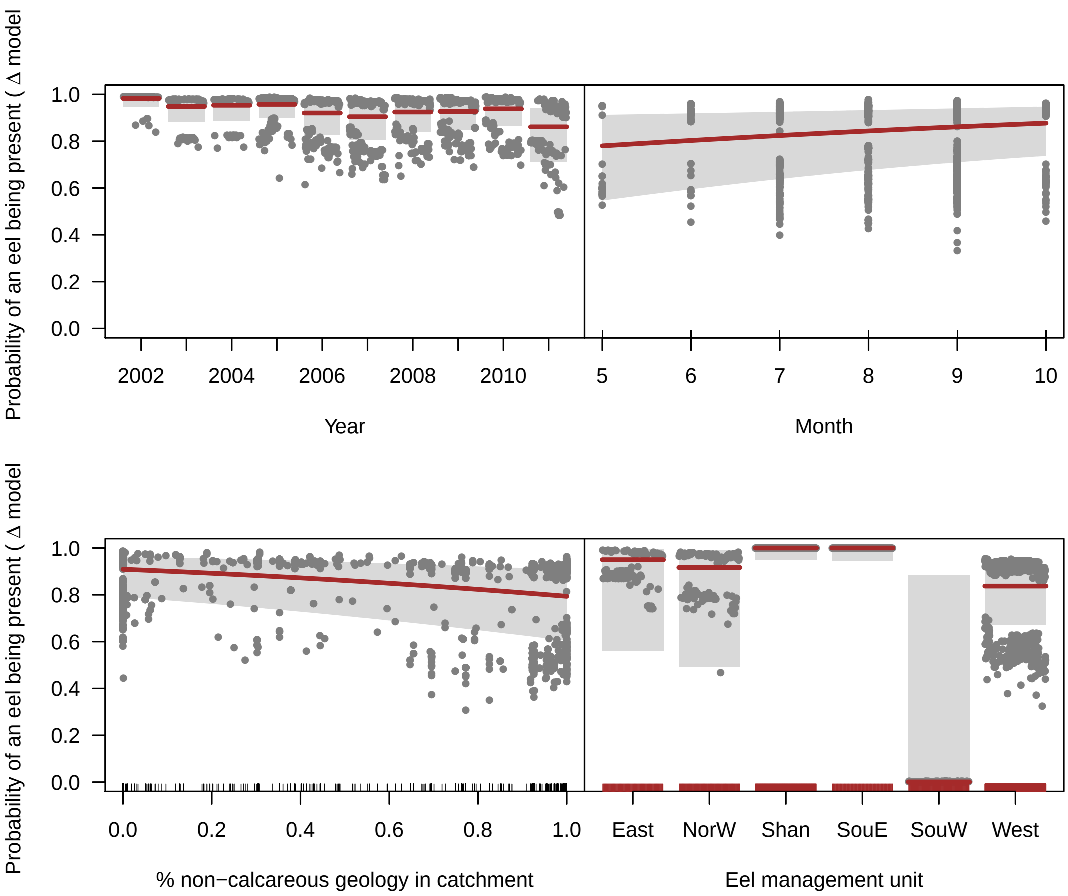


Figure 3.8: Partial residuals of each variable included in the Δ model (apart from distance to the sea)

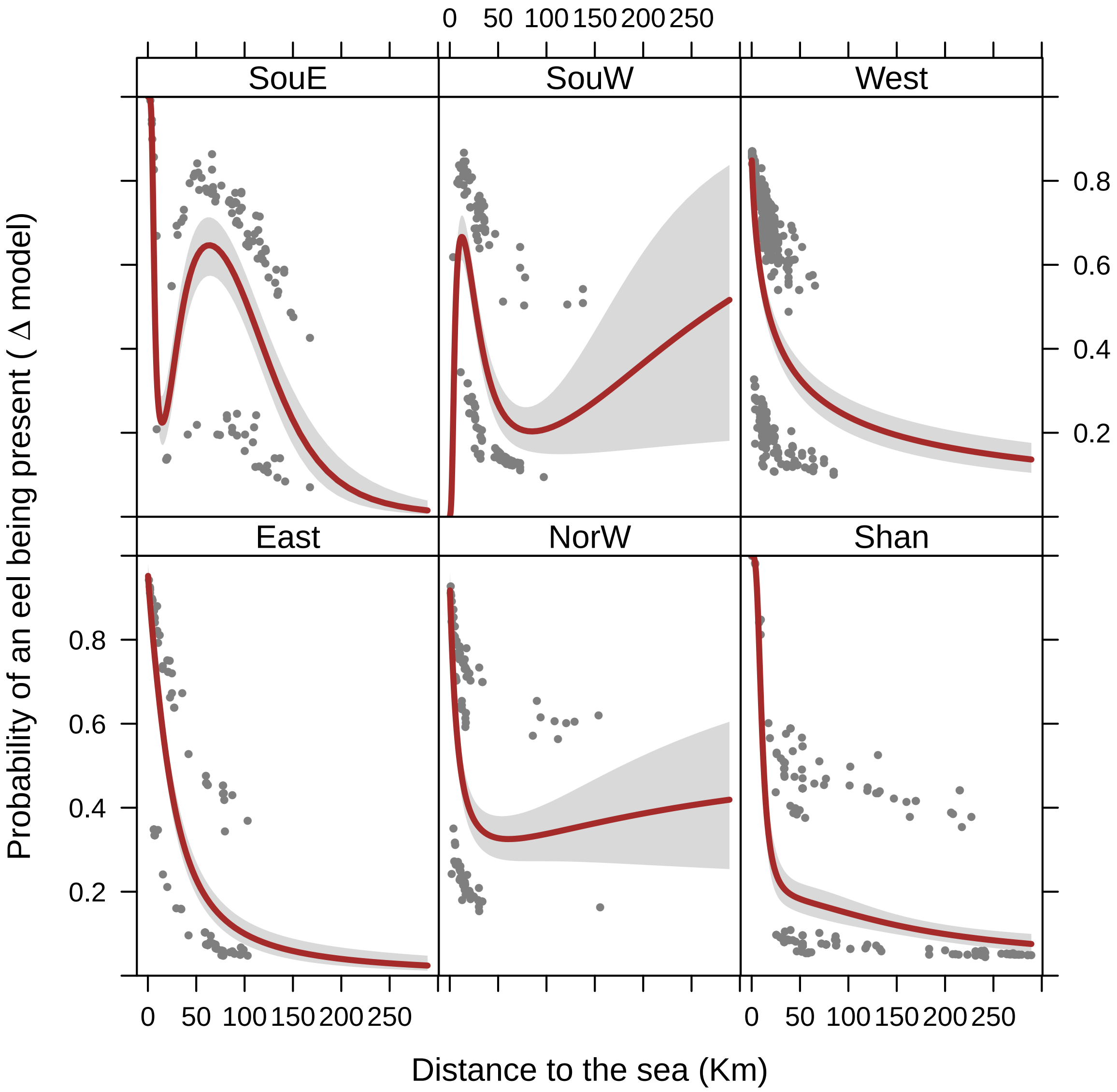


Figure 3.9: Partial residuals of each variable included in the Δ model - Distance from the sea accoring to EMU

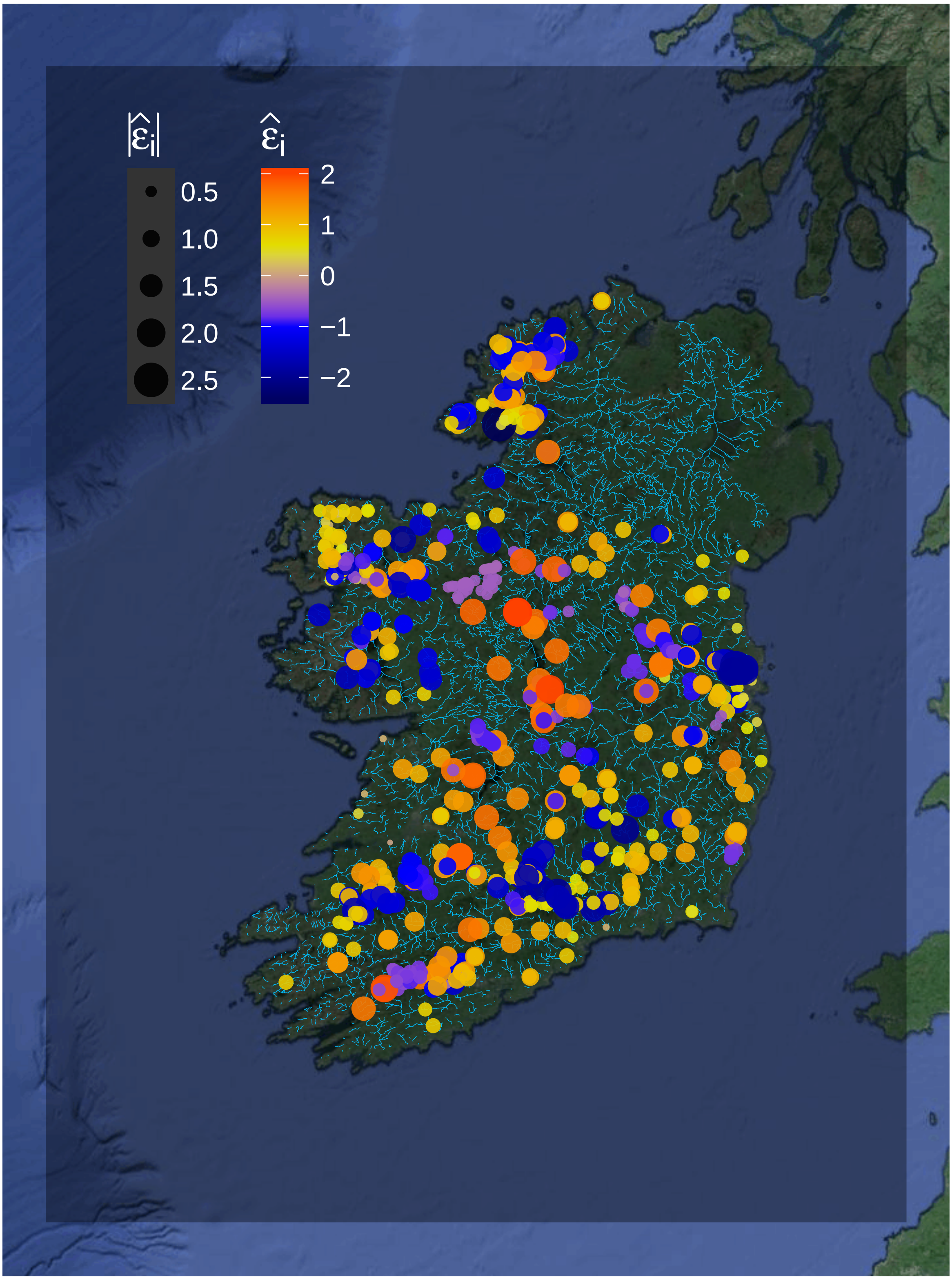


Figure 3.10: Residuals from the Δ model corresponding to observed -predicted values, hence a blue spot (negative value) will indicate a predicted value larger than the observed one, and a red point (positive value) a predicted value lower than the observed one (Map 3.10).

Table 3.2: Regression analysis for the presence absence (Δ) model

	Dependent variable:
	d != 0
Intercept	1.205 (0.699)
Year 2003	−1.121 (0.511)*
Year 2004	−1.009 (0.539)
Year 2005	−0.919 (0.482)
Year 2006	−1.583 (0.479)***
Year 2007	−1.782 (0.463)***
Year 2008	−1.523 (0.465)**
Year 2009	−1.487 (0.464)**
Year 2010	−1.311 (0.478)**
Year 2011	−2.204 (0.505)***
month	0.140 (0.064)*
p_non_calc_surf	−0.957 (0.197)***
	estimated degrees of freedom
s(log distance_sea):_East	1.304***
s(log distance_sea):_Northwest	1.847*
s(log distance_sea):_Shannon	2.670***
s(log distance_sea):_Southeast	2.883*
s(log distance_sea):_Southwest	2.731**
s(log distance_sea):_West	1.000***
Observations	1438
Adjusted R^2	0.159
Explained Deviance	0.139
Note:	*p<0.1; **p<0.05; ***p<0.01

3.3.2.2 Positive densities - Γ model

The model, calibrated with postive densities values, used results from 821 electrofishing surveys. The best density model was:

$$Density \sim year + month + EMU + p\ non\ calc\ surf + s(log(distance\ to\ sea\ by\ EMU, 3)$$

The percentage of deviance explained by the model was 26% (Table 3.3). The partial residuals of the model shows the effect each variable has on the model results (Figure 3.11, 3.12). Owing to transport operations of recruits in the Shannon and Erne, it was necessary to include EMU as a variable, as these two EMU's responded differently in the model.The residuals from the density model don't show any pattern across the country, which is good. If residuals had shown a clumping in certain geographical areas, this would indicate that another explanatory variable, not included in the analysis might be needed (Figure 3.13). The densities predicted by the Γ model are highest in the Southeast EMU, and in river segments draining into the Shannon estuary. (Figure 3.14)

Table 3.3: Regression analysis for the density (Γ) model

	Dependent variable:
	d
Intercept	0.905 (0.459)*
Year 2003	−1.110 (0.237)
Year 2004	−0.156 (0.249)
Year 2005	−0.049 (0.212)
Year 2006	−0.273 (0.228)
Year 2007	−0.438 (0.206)*
Year 2008	−0.813 (0.209)***
Year 2009	−0.881 (0.203)***
Year 2010	−0.841 (0.218)***
Year 2011	−0.098 (0.260)
month	0.069 (0.048)
Northwest EMU	−0.244 (0.241)
Shannon EMU	0.533 (0.264)*
Southeast EMU	1.397 (0.311)***
Southwest EMU	0.409 (0.309)
West EMU	0.423 (0.209)*
p_non_calc_surf	−0.293 (0.133)*
	estimated degrees of freedom
s(log distance_sea):_East	1.000***
s(log distance_sea):_Northwest	1.641***
s(log distance_sea):_Shannon	1.714***
s(log distance_sea):_Southeast	1.00***
s(log distance_sea):_Southwest	1.999***
s(log distance_sea):_West	1.631
Observations	821
Adjusted R^2	0.25
Explained Deviance	0.26
Note:	*p<0.1; **p<0.05; ***p<0.01

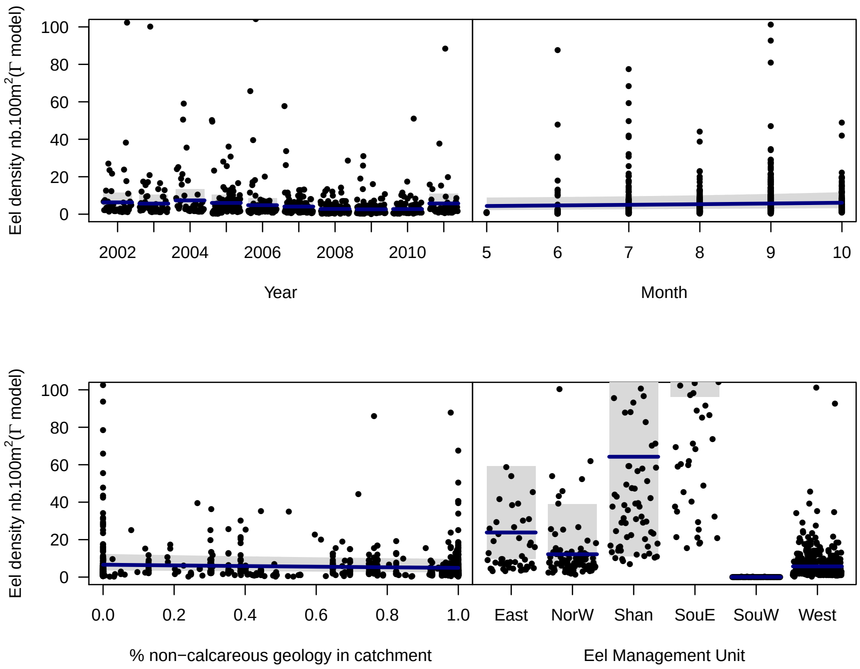


Figure 3.11: Partial residuals of four variables included in the generalized additive model (GAM) for the density model (Γ)(apart from distance to the sea).

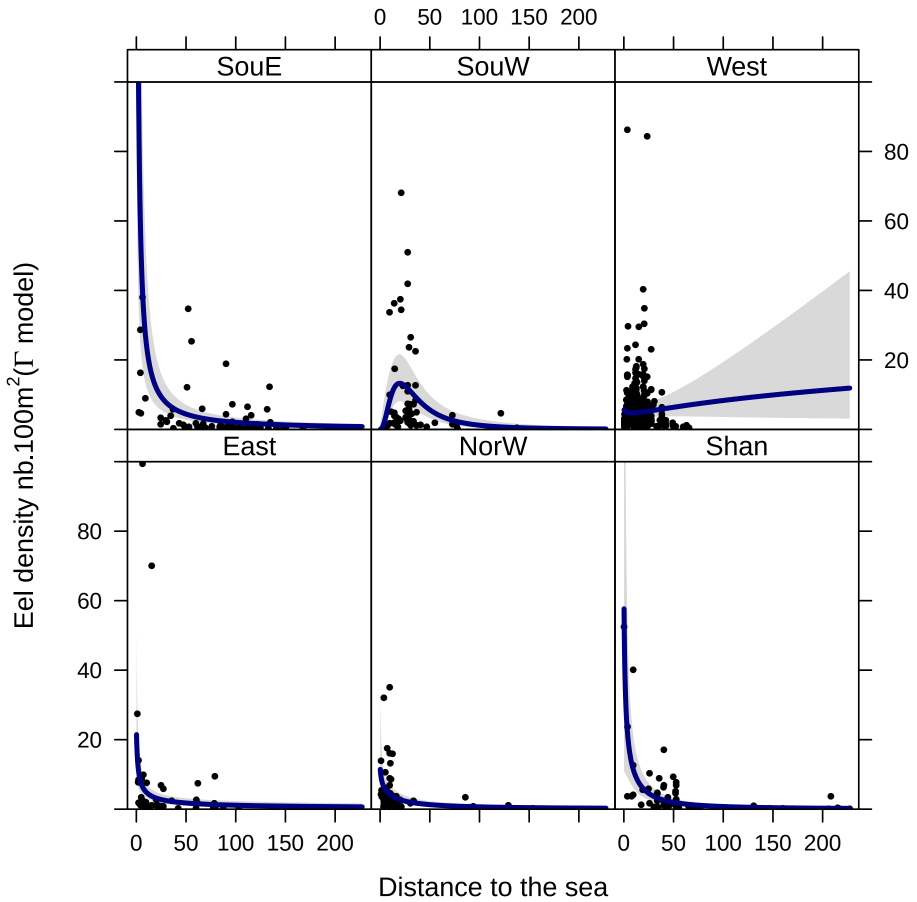


Figure 3.12: Partial residuals of each variable included in the generalized additive model (GAM) for the density model (Γ) - distance to the sea accoing to EMU.

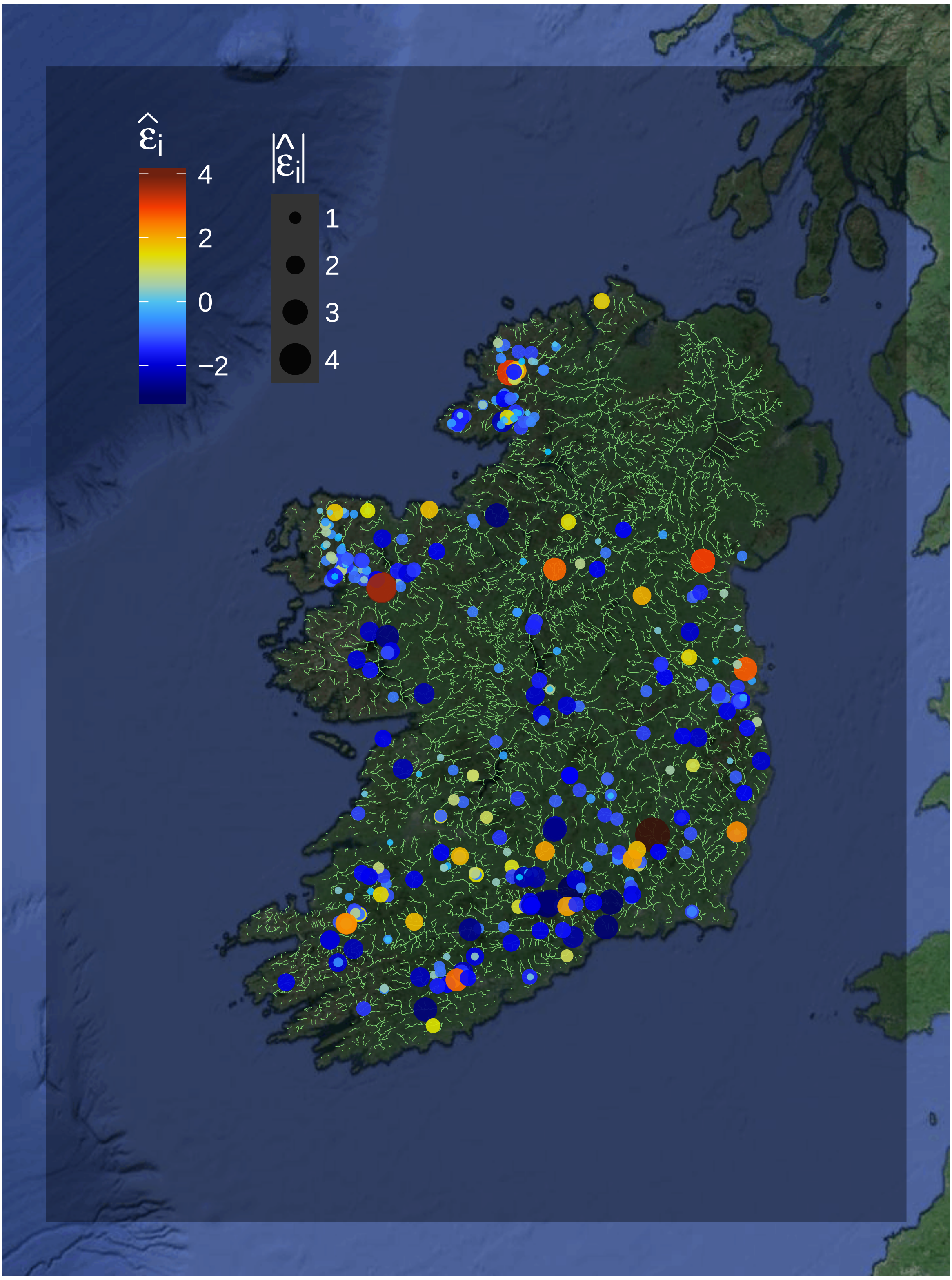


Figure 3.13: Residuals from the Γ model = predicted-observed $\epsilon\hat{}_i$, absolute-residuals values $\epsilon\hat{}_i$. The residuals correspond to the mean values of all the residuals for one station (if several electrofishing occured a the same site). The size of the points gives an indication of how many electrofishing operations occurred at that point and thus of the 'weight' of that station in the model (Map 3.13).

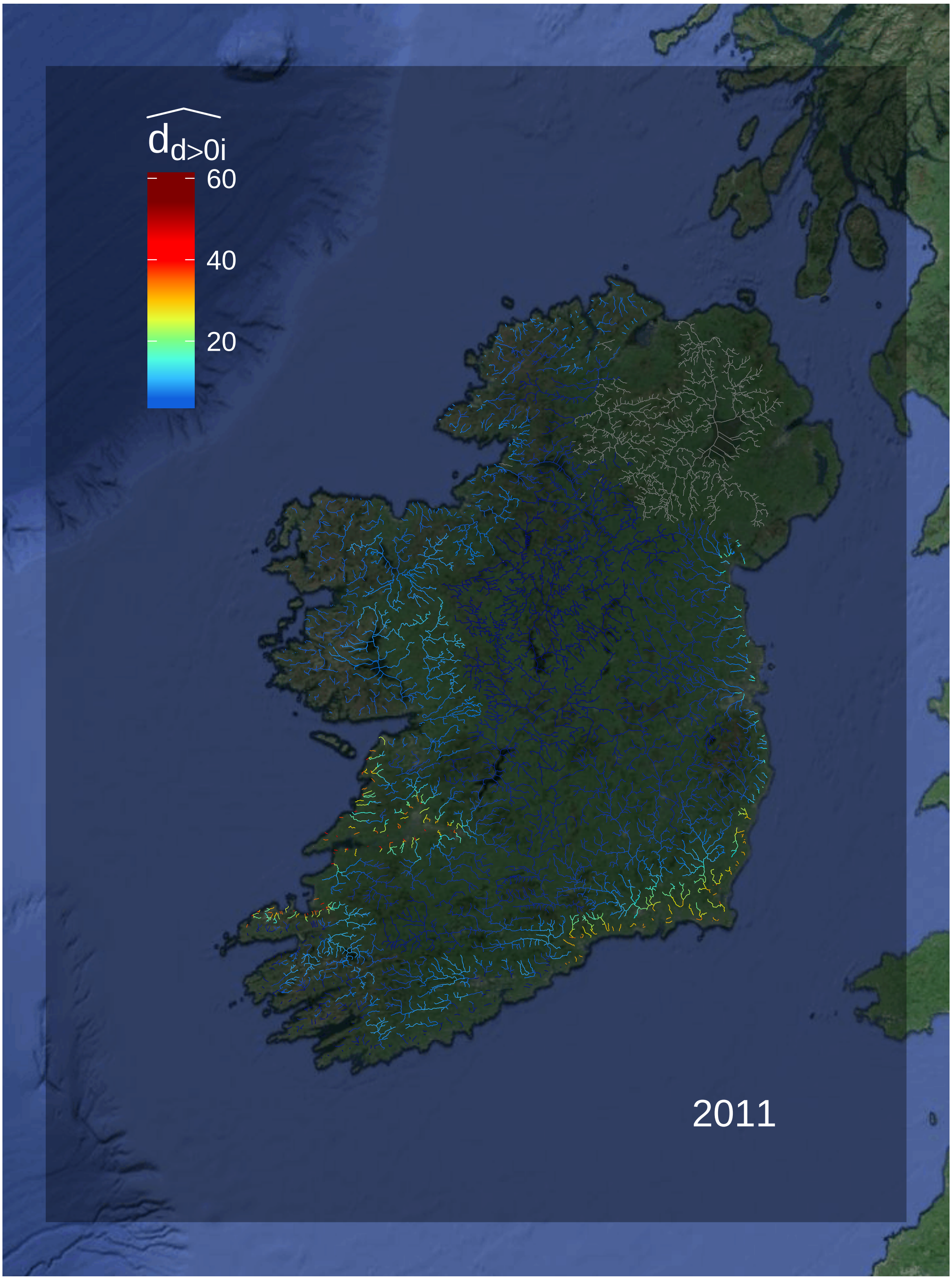


Figure 3.14: Densities predicted by the Γ model in eel.100m^{-2} in 2011. Note these correspond to the prediction of the Γ model for positive values only. These values have to be multiplied by the Δ model to produce the final results.

3.3.2.3 Final - ΔΓ model

The final model is the product of the Δ model by the Γ model. The Δ model is the probability of having a positive density. The Γ model is the fitting of densities for positive values, given that the data are log-normally distributed. (3.15).

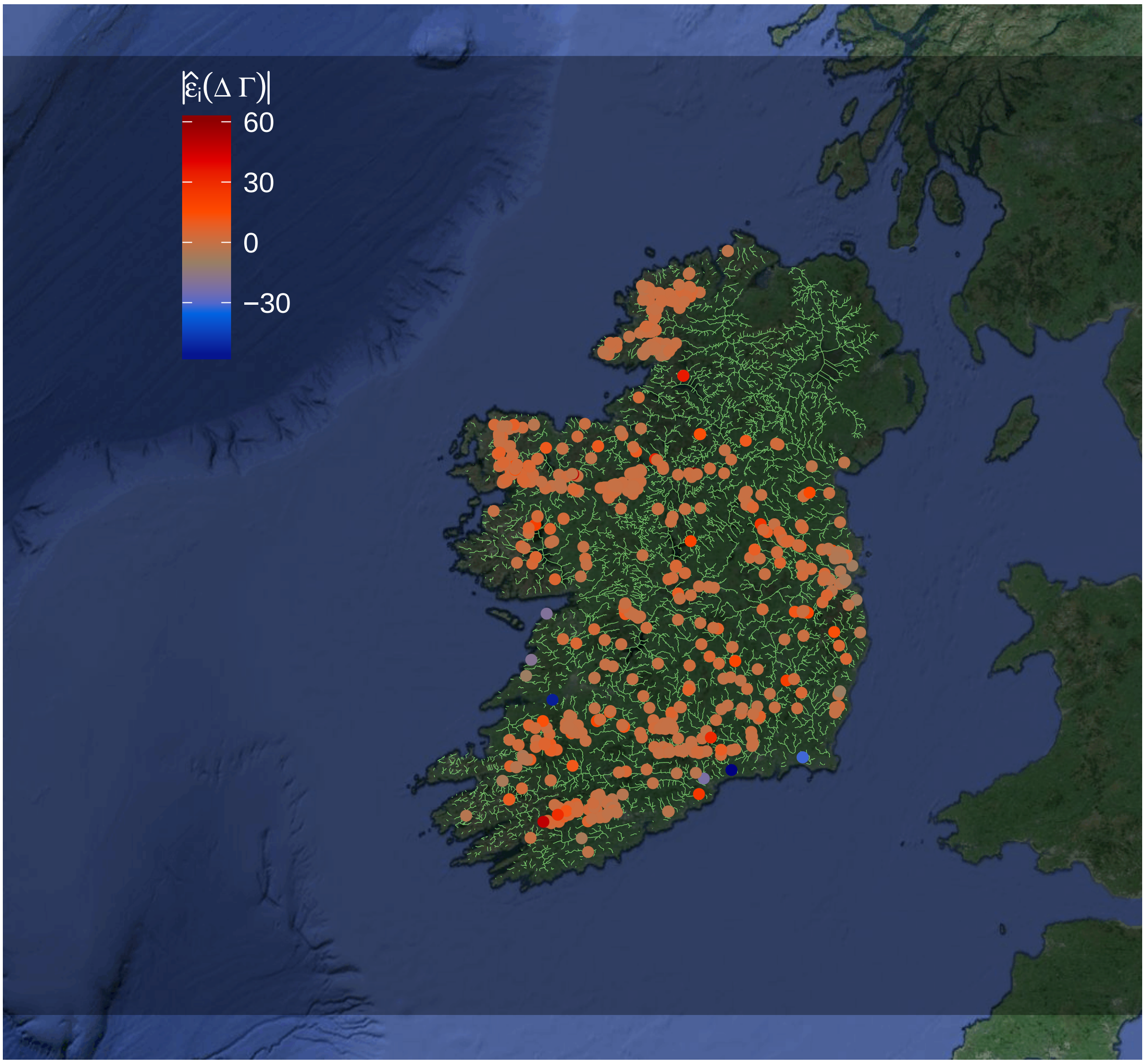


Figure 3.15: residuals for the Δ Γ model calculated as observed-Δ∗Γ . Size and color according to the residual value. Average values calculated are low so the range of residuals is biased toward large positive results.

3.4 Predictions

3.4.1 Stock

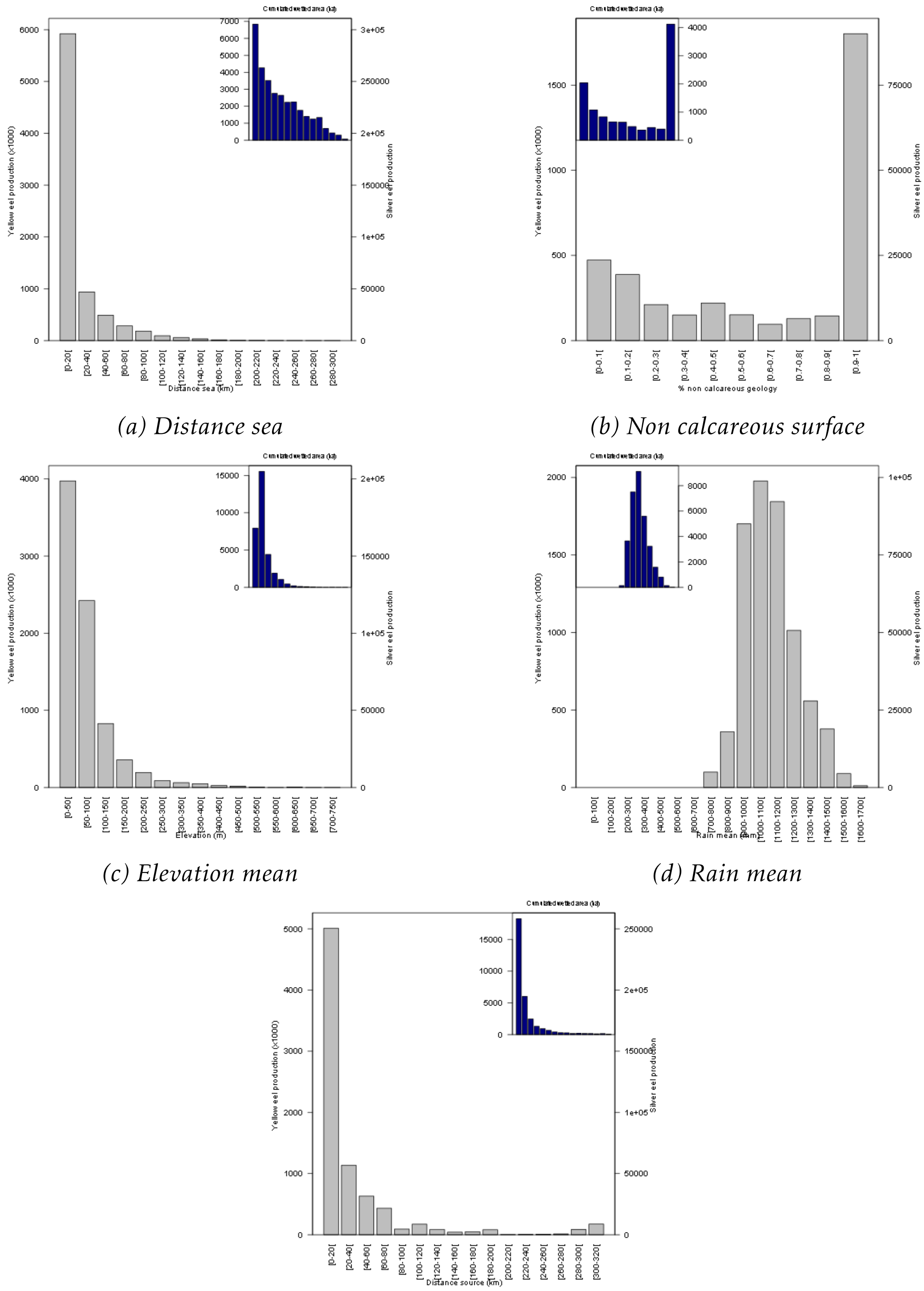
The predictions from the river width model were applied to every river segment in the CCM dataset, in order to quantify the fluvial habitat available to eel, according to EMU (Table 3.4).

Table 3.4: Water surface and eel abundance in Irish EMUs, predictions for year 2011. Density is that of yellow eel in river segments

Emu	River area (km2)	Yellow eel	Silver eel	Density (eel.100m-2)
NorW	42.15	505748	12644	1.542
West	37.39	1151735	28793	3.018
Shan	153.61	3612625	90316	3.090
SouW	29.32	795745	19894	2.477
SouE	30.04	1466354	36659	8.841
East	25.18	500627	12516	1.896
All	317.69	8032834	200821	3.547

3.4.1.1 Predictions for 2011

The abundance and density of eels was predicted for 2011. The models predict that the fluvial habitat of Ireland contained 8,032,834 yellow eels corresponding to 200,821 silver eels using a silvering rate of 2.5% (Table3.4). The relationship between the distribution of eels and the various explanatory variables are shown in Figure 3.16. Den-sities and abundance of yellow eels are, as expected, higher closer to the sea, along the south coast and into the Shannon estuary (Map 3.17). For the majority of the country, EDA predicts less than 5 eels per 100 m² (Map 3.17).



(a) Distance sea

(b) Non calcareous surface

(c) Elevation mean

(d) Rain mean

(e) Distance source

Figure 3.16: Distribution of yellow eels and silver eels abundance predicted in 2011, on the CCM dataset. The results are classified according to the distribution of the variables used in the model. The box in the upper right corner of each graph shows the occurrence of the corresponding class of the variable in the Irish CCM dataset

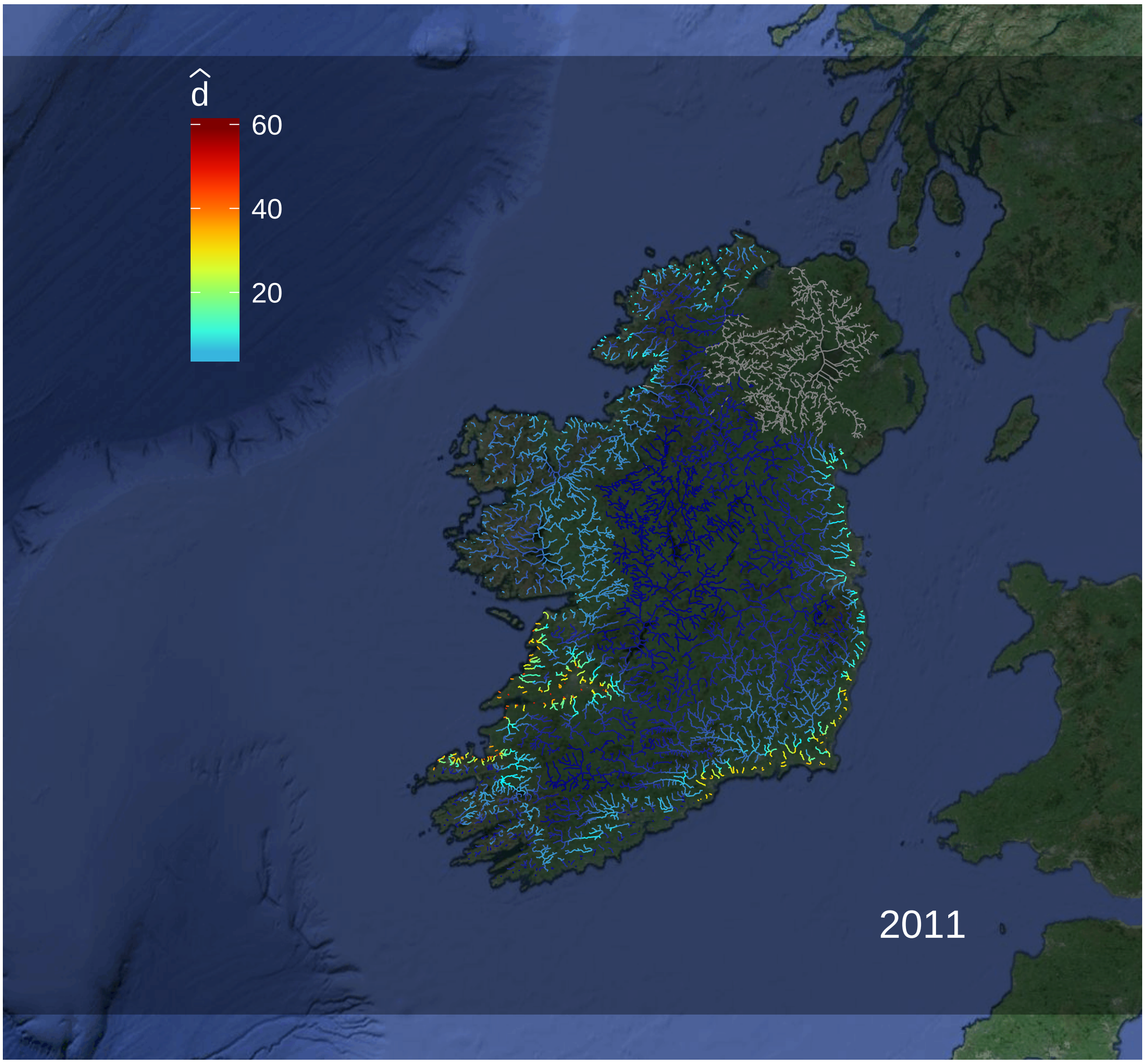


Figure 3.17: Yellow eels densities (eel.100m^{-2}), predicted by the $\Delta\Gamma$ model for 2011.

3.4.1.2 Predictions for the last 10 years

Based on electrofishing data from the last ten years, EDA predicts a total of 13,130,233 yellow eels in the fluvial habitat at the start of the time series, followed by a decrease to 39% of the 2002 value, and a minimum stock of 4708270 yellow eels in 2010. The stock appears to have increased in 2011 (Figure 3.18). The largest contribution to the Irish Eel production comes from the Shannon EMU. Figure (3.19) shows the annual range of predicted density per river segment, with the majority of river segments containing between 1 and 5 yellow eels per 100 m².

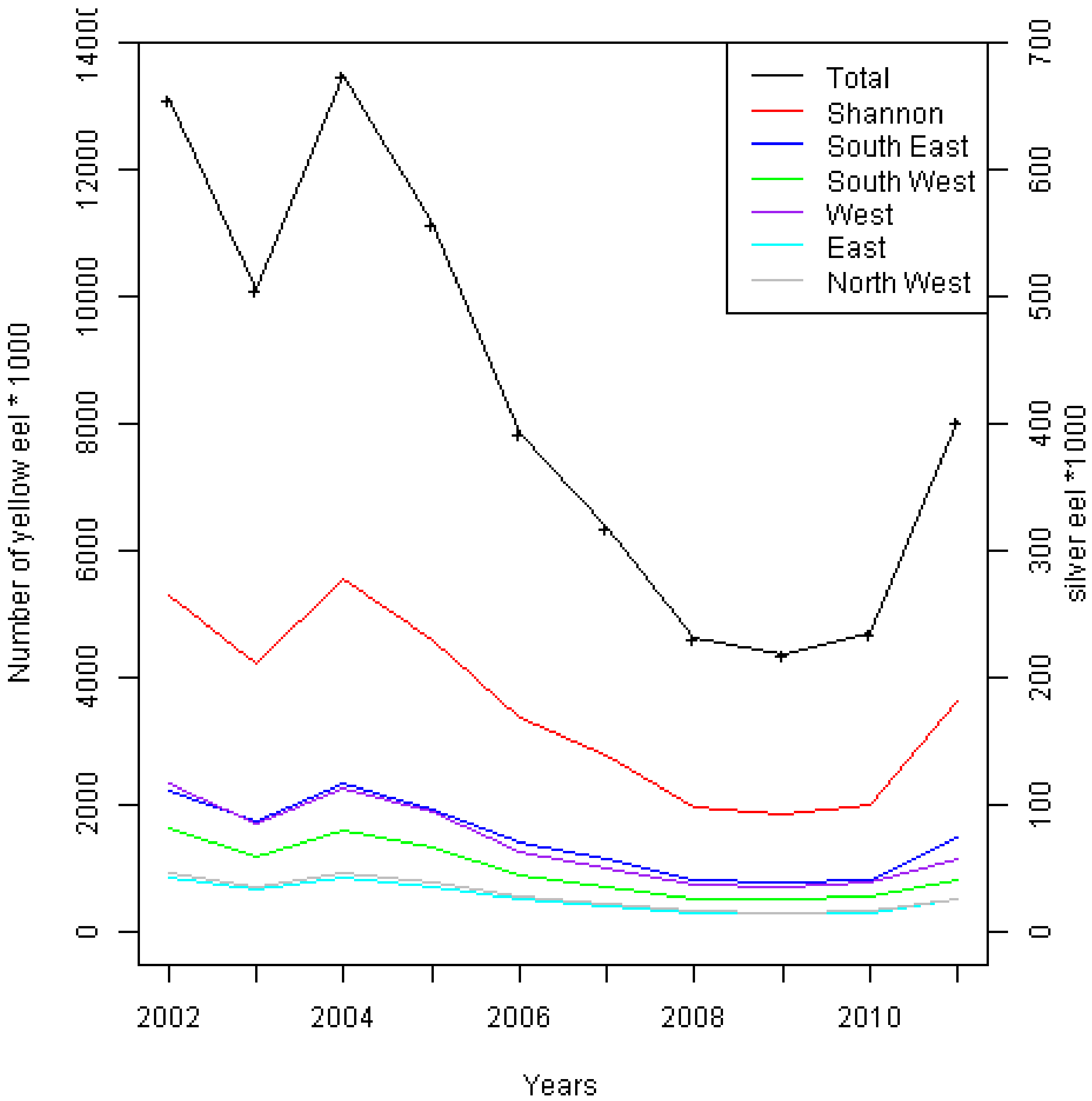


Figure 3.18: Number of yellow and silver eels predicted per year in Ireland's rivers.

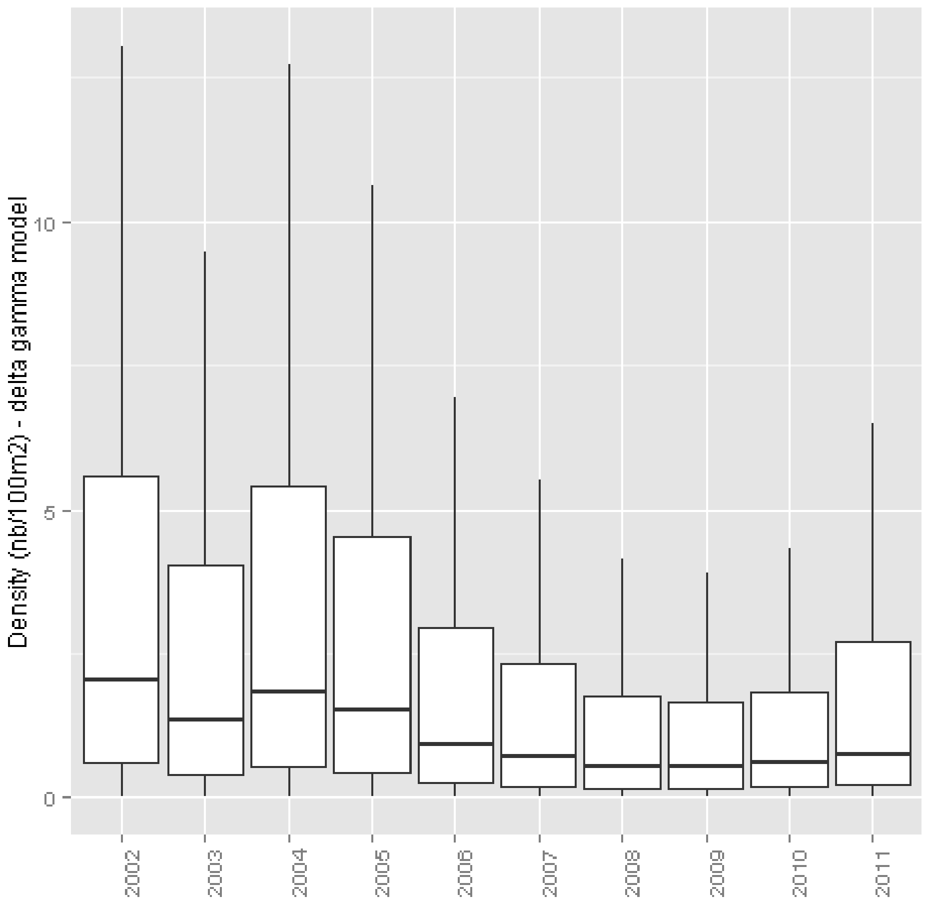


Figure 3.19: Boxplot of the number of yellow eels predicted in each river segment in Ireland, expressed as density per 100 *m² per year in Ireland*

3.4.2 Escapement

The biological and mortality parameters used to calculate stock indicators were collated from a variety of sources and are summarised in table 3.5. Stock indicators used to draw the precautionary diagrams (Figures 3.20 - 3.25) are presented in Annex 1. These precautionary diagrams are based on the fluvial portion of the eel populations only. B0 has been adjusted according to the percentage of fluvial havitat in each EMU to reflect this. In contrast, Figure 3.26 and table 3.6 includes lake production estimates, and presents the stock indicators for all EMU's calculated for 2011. In this case B0 is the pristine spawner escapment estimate for total production from each EMU, as reported in the National Eel Management Plan (Anon., 2008) and in the WKEPEMP report (ICES, 2013).The WKEPEMP report was published by ICES, and collates stock indicators for all EMU's across Europe and are the most recently available stock indicators calculated for Ireland (for the year 2011) by the SSCE (Standing Scientific Committee on Eel) (Anon., 2012). Table 3.6 shows the differences in stock indicators cal-culated using three different methods. The first row for each EMU (2012) were taken from the WKEPEMP report (ICES, 2013), The stock indicators were calculated using the Irish model formulated during preparation for the publication of the National Eel Managament Plan (Anon., 2008). The second row for each EMU are the stock indicators calculated in this current analysis, which apply only to the fluvial portion of the eel populations in each EMU. Finally, the third row gives an indication of how different these stock indicators would be if an estimate of lake production is included, based on the analysis outlined in section 2.3.2.

Table 3.5: Parameters used to predict escapement

Parameters	NorW	West	Shan	SouW	SouE	East
Year	2011	2011	2011	2011	2011	2011
M(Natural mortality)	0.139	0.139	0.139	0.139	0.139	0.139
Life river (years)	18	18	18	18	18	18
Age catch (years)	13	13	13	13	13	13
Weight glass eel (Kg)	0.000334	0.000334	0.000334	0.000334	0.000334	0.000334
Weight yellow eel (Kg)	0.17	0.17	0.17	0.17	0.17	0.17
Weight silver eel (Kg)	0.253	0.215	0.253	0.213	0.213	0.174
tau silver	0.025	0.025	0.025	0.025	0.025	0.025

Table 3.6: Stock indicators in Ireland, comparison with previous EU reporting and between fluvial and fluvial + lake estimate, Bcurrent is colour coded according to whether it is greater than (green) or less than (red) the biomass target set by the EU Regulation. Note that grey values indicate that Bcurrent is larger than B0. ΣA is colour coded according to whether it is less than (green) or greater than (red) the mortality target equivalent to the biomass target (after (ICES, 2012) for ΣA). The amount of restocked eel is presented in glass eel equivalents, to standardize for eel ongrown before restocking. Note that the target for ΣA is lower than 0.92 if $B_{current} < 0.4B_0$.

			Biomass (t)			**Mortality**		
	Source	Year	$B_{current}$	B_{best}	B_0	ΣF	ΣH	ΣA
NorW								
	2012	2011	51.5	54.3	135.8	0	0.05	0.05
	2015 flu	2011	2.9	2.9	13.6	0	0.01	0.01
	2015 flu+lake	2011	42.4	58.0	135.8	0	0.31	0.31
West								
	2012	2011	68.7	68.7	189.2	0	0.00	0.00
	2015 flu	2011	5.5	5.5	13.2	0	0.00	0.00
	2015 flu+lake	2011	60.1	60.1	189.2	0	0.00	0.00
Shan								
	2012	2011	68.7	75.4	201.2	0	0.09	0.09
	2015 flu	2011	7.6	7.6	22.1	0	0.00	0.00
	2015 flu+lake	2011	72.6	79.1	201.2	0	0.09	0.09
SouW								
	2012	2011	11.3	11.6	24.5	0	0.03	0.03
	2015 flu	2011	4.5	4.5	7.1	0	0.01	0.01
	2015 flu+lake	2011	13.8	14.4	24.5	0	0.05	0.05
SouE								
	2012	2011	6.8	6.8	14.8	0	0.00	0.00
	2015 flu	2011	10.5	10.5	14.2	0	0.00	0.00
	2015 flu+lake	2011	10.7	10.7	14.8	0	0.00	0.00
East								
	2012	2011	9.4	9.6	20.5	0	0.01	0.01
	2015 flu	2011	1.9	1.9	6.4	0	0.00	0.00
	2015 flu+lake	2011	6.5	7.1	20.5	0	0.09	0.09

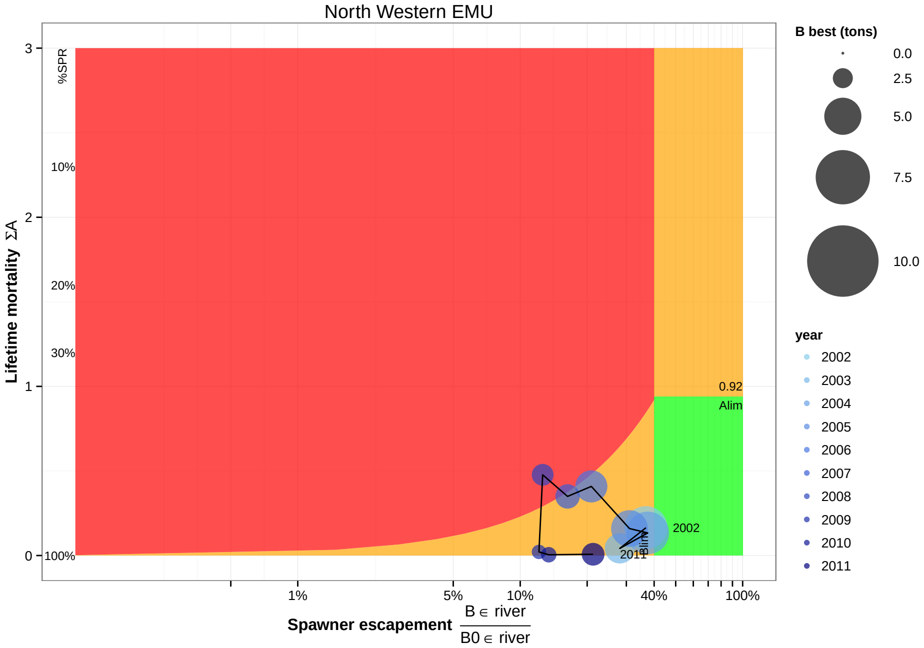


Figure 3.20: Precautionary diagram for the North Western EMU. These stock indicators are calculated for the FLUVIAL eel populations in the EMU, and do not include lake populations.

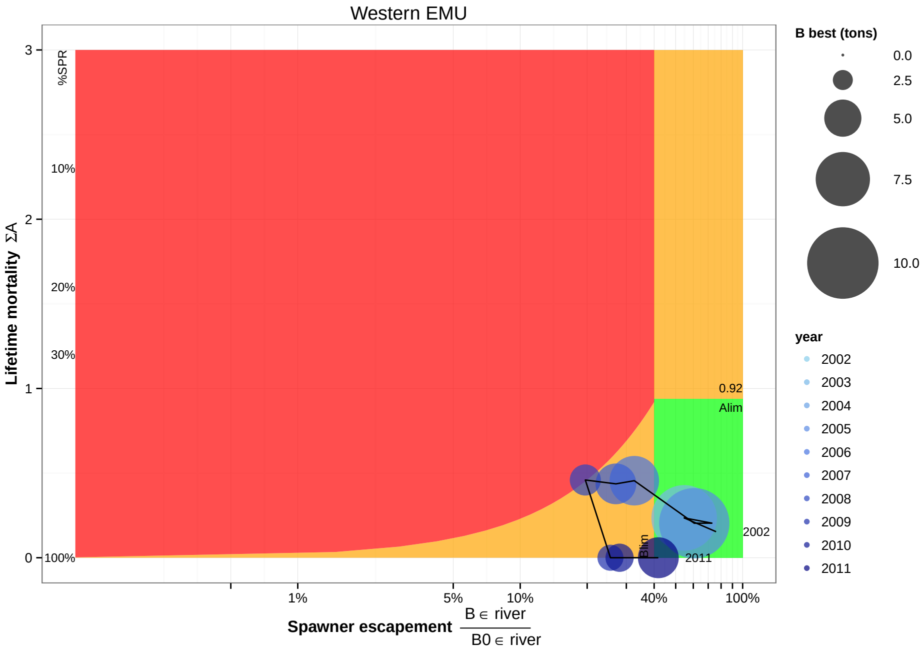


Figure 3.21: Precautionary diagram for the Western EMU. These stock indicators are calculated for the FLUVIAL eel populations in the EMU, and do not include lake populations.

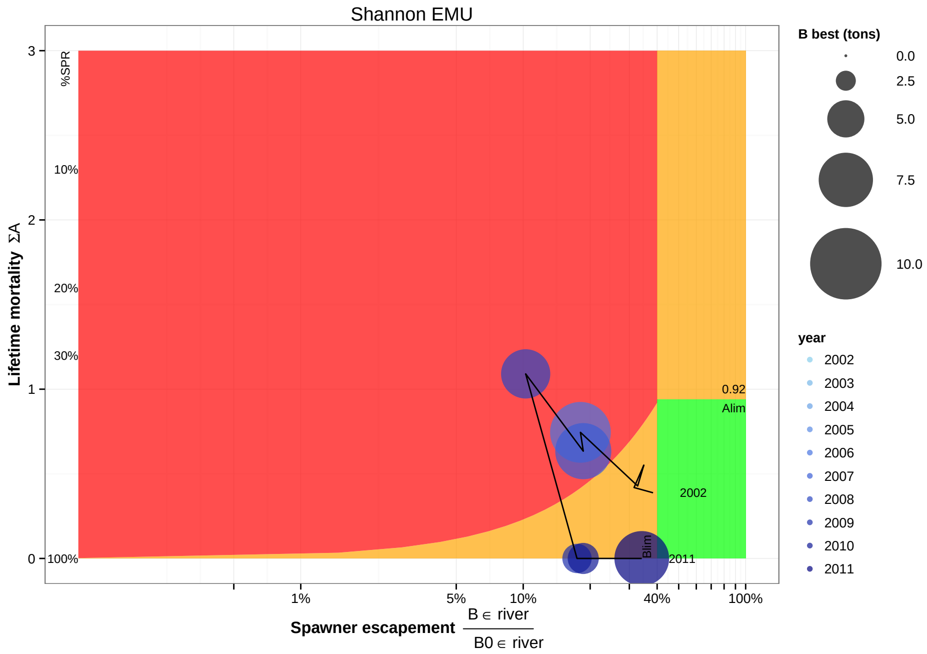


Figure 3.22: Precautionary diagram for the Shannon EMU. These stock indicators are calculated for the FLUVIAL eel populations in the EMU, and do not include lake populations.

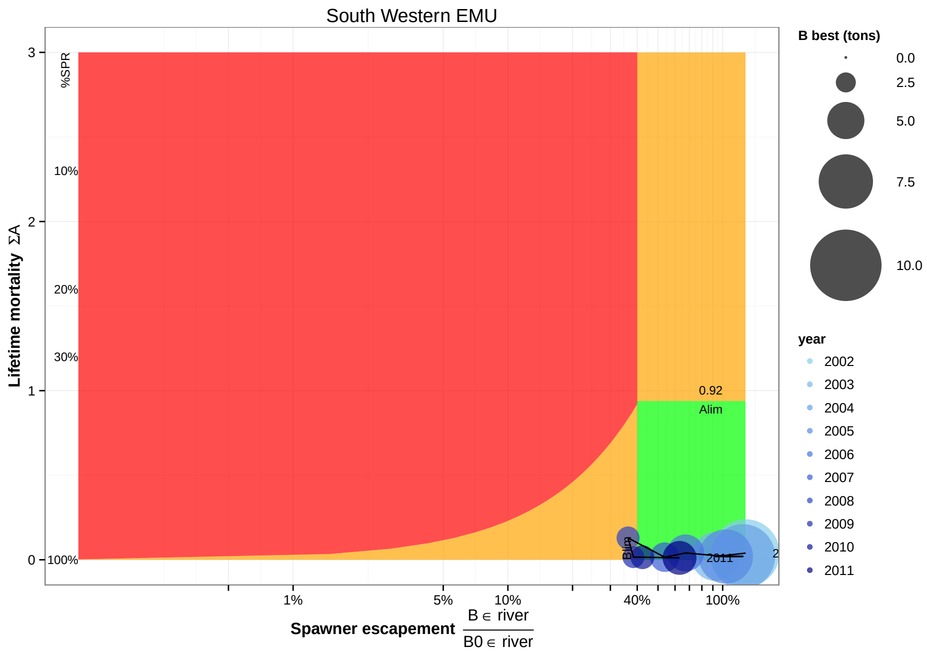


Figure 3.23: Precautionary diagram for the South Western EMU. These stock indicators are calculated for the FLUVIAL eel populations in the EMU, and do not include lake populations.

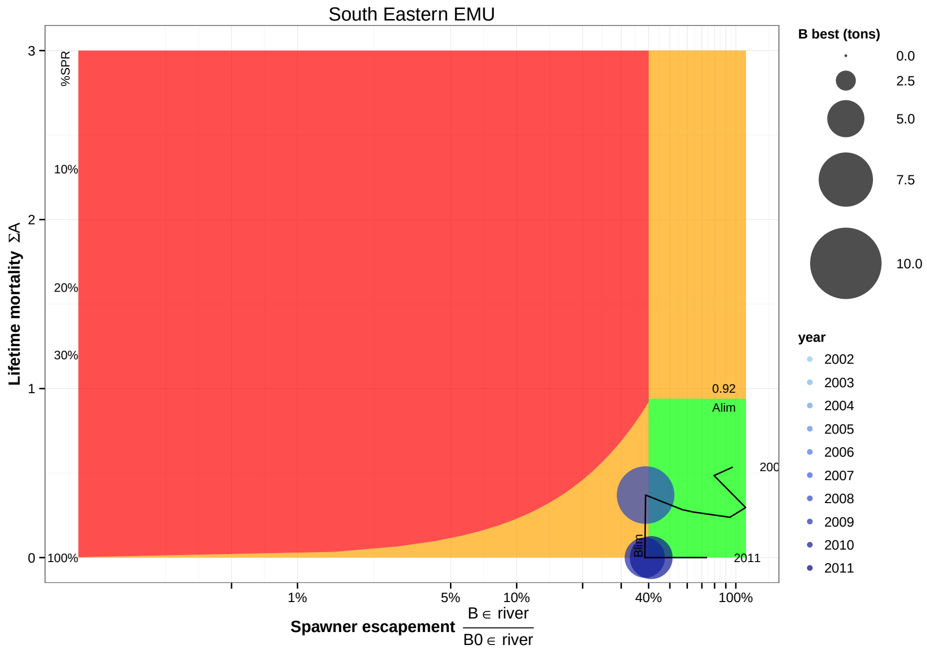


Figure 3.24: Precautionary diagram for the South Eastern EMU. These stock indicators are calculated for the FLUVIAL eel populations in the EMU, and do not include lake populations.

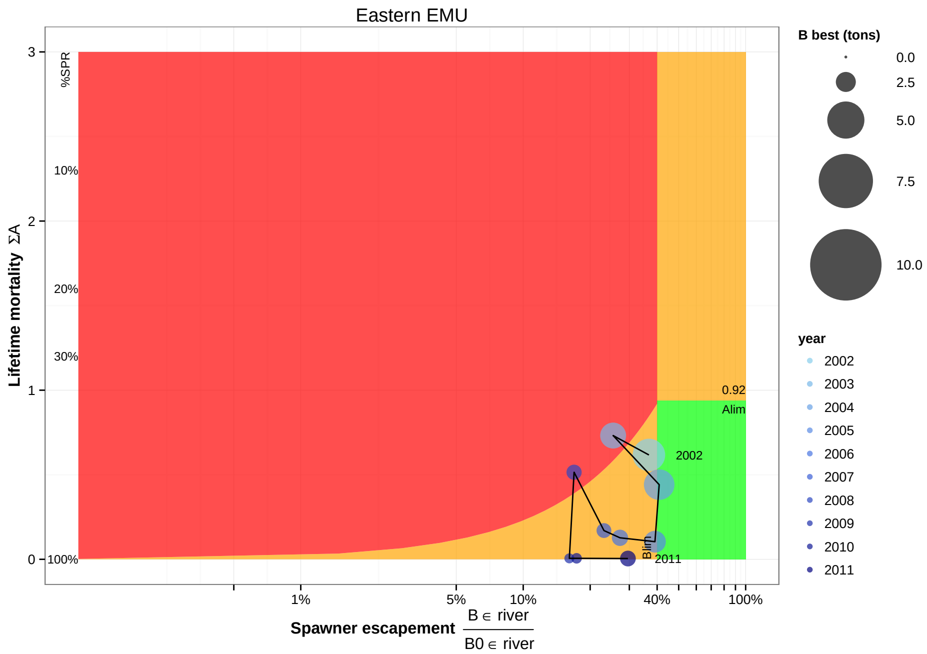


Figure 3.25: Precautionary diagram for the Eastern EMU. These stock indicators are calculated for the FLUVIAL eel populations in the EMU, and do not include lake populations.

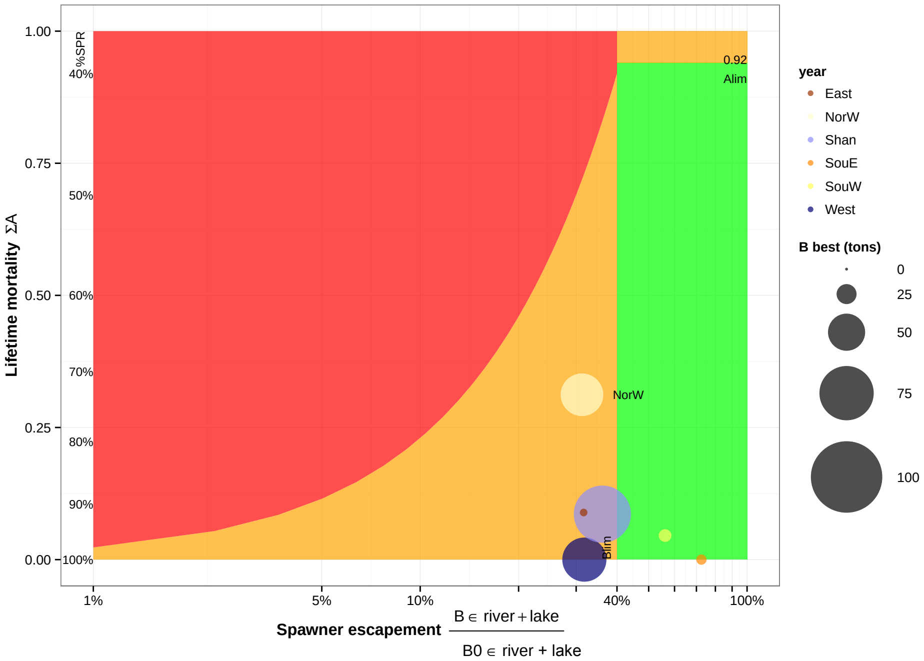


Figure 3.24: Precautionary diagram for 2011, for all EMUs. These stock indicators are the sum of fluvial and lake production estimates.

Discussion

4.1 Relationship between eel density and explanatory variables

The explanatory variables that were used to predict the abundance and density of eel in Ireland included year, distance from the sea, the type of geology in the catchment, the time of year and finally EMU. None of these variables are particularly surprising, and the inclusion of several of these are in agreement with previous analyses of fluvial eel distribution in Ireland and abroad. It has been previously noted that eel density tends to be higher in catchments with some calcareous geology (Anon., 2008), presumably owing to higher availability of food and more hospitable growing condi-tions. Many studies have highlighted the tendancy for eel density and abundance to decrease as distance to the sea increases, with highest densities being recorded more often near the tidal limit (Naismith and Knights, 1993). The inclusion of 'month' as an explanatory variable may be an artefact of the data collated, with a bias towards sampling in late summer. It is, however, possible that eel densities may vary in fluvial habitats as the year progresses, and yellow eels begin to silver and migrate towards the sea. Finally, the inclusion of EMU is warranted as several EMU's displayed vary-ing responses in terms of eel density and abundance. The most likely reason for this is the presence of obstructions (for example Ardnacrusha or Cathleen's Falls), which may artifically affect how eels distribute themselves with a catchment. It is also likely that the role of anthropogenic transport of juvenile eel around obstructions leads to unnatural patterns in abundance and density.

4.2 Comparison with other estimates of stock indicators

It is very encouraging to see that the stock indicators calculated using EDA and a proxy for lake productivity are quite similar to those previously calculated for Ireland (Table 3.6). The best example of this is for the Southeastern EMU, which has a very small proportion of lacustrine habitat (4%). The EDA fluvial estimate of $B_{current}$ for the South-eastern EMU is 6.4 tonnes for 2011, while the Irish model (Anon., 2012) predicted $B_{current}$ at 6.8. Both of these estimates exceed the biomass target (40%) set by the EU regulation.

These two statistical methods use very different data in their calculation, and the fact that they are very similar gives some confidence that production value for the Southeastern EMU is correct. Similarly, when we add in lake production, the estimates of $B_{current}$ for all EMU's are roughly similar, and, with one exception, give the same indication of whether the biomass target is being met (i.e. they are given the same colour coding in Table 3.6). The only exception is the Eastern EMU, where the Irish model estimate of $B_{current}$ is 9.4 tonnes, which is greater than 40% of the target, while the EDA model (flu + lake) gives an estimate of 6.5 tonnes, which is below the biomass target. In comparing the Irish model estimate with the EDA (flu + lake) estimate, we note that the raw data used to calculate lake production comes from the same source for the two models (i.e. total production from the Burrishoole, Shannon, Corrib and Erne catchments). However, the treatment of this data differs considerably between the two models, and again, this gives confidence that both estimates are in the correct range. This is a significant result as the estimation of eel production from EMU's is inherently difficult. The fact that we have two models giving roughly similar estimates strengthens the assessment of eel production from Ireland, and gives us complimentary methods with which to assess the success of future management actions. As EDA is run on current (or recent) surveys of yellow eel densities, we expect that any increase or decrease in recruitment in the coming decades will be captured by this model, allowing comparison with B_0 in the future.

4.3 Mortalities and management issues

Table 3.6 shows the current mortalities calculated using different modeling methods. Currently, the only mortalities are the result of hydropower turbines (H), and this occurs in four of the EMUs (North West, Shannon, Southwestern and Eastern). Eel fishing has been suspended in Irish waters since the implementation of the Eel Management Plan, and so fishing mortality (F) is 0 in all cases. The precautionary diagrams using time series of fluvial estimates (Figures 3.20 - 3.25) show how these mortalites and managment actions have affected the indicator B_{best}, with all EMUs displaying the same pattern of lifetime mortality decreasing towards the bottom of the y-axis, and hence $B_{current}$ approaching B_{best}. If the increase in juvenile recruitment which has been noted in recent years continues (ICES, 2013), we would expect the EDA model of fluvial production to adequately capture any increase in B_{best}. The development and continued use of EDA is therefore warranted for Ireland, and some of the work that could be done in the future is outlined in the next section. Continued use of EDA is reliant on continued broadscale electrofishing coverage.

4.4 Bias and limits of the work

During the process of applying EDA to Ireland, some limitations were encountered. Rather than focussing on how these limitations undermine the results presented here, in this section we discuss how these limitations can be overcome in order to make the next EDA run more applicable.

4.4.1 Using a better resolution GIS coverage to calculate water surface

The first possible bias is a problem with the GIS coverage used to extrapolate densities in the model. The CCM largely underestimates the river habitat in upper reaches of the catchments, by not including first order streams. In addition, the CCM includes river segment travelling the length of lakes, so when there is a large lake at the bottom of a catchment, the predicted river width of this in-lake river segment can be large, thus overestimating the fluvial habitat (Figure 4.1). The river widths calculated here are different to those described in (McGinnity et al., 2012), which is not surprising con-sidering the differences between the two GIS coverages used to compute the predicted river widths. Interestingly, the models described in (McGinnity et al., 2012) and in this document both use upstream catchment area as the primary explanatory variable. However, the Baseline GIS layer used in (McGinnity et al., 2012) was the Irish Ordnance Survey River Network, which is fundamentally more applicable to the actual habitat occupied by Eel in Ireland. Utilisation of this GIS layer in future runs of EDA will undoubtedly lead to more accurate predictions of eel numbers in fluvial habitat. In this report, we overcame this diffculty by raising the CCM wetted area by the ratio between CCM wetted area and OS wetted area, measured at the EMU scale. While this is not an ideal way of correcting for the difference between the two coverages, it gives a better estimate than just using the CCM estimate of wetted area.

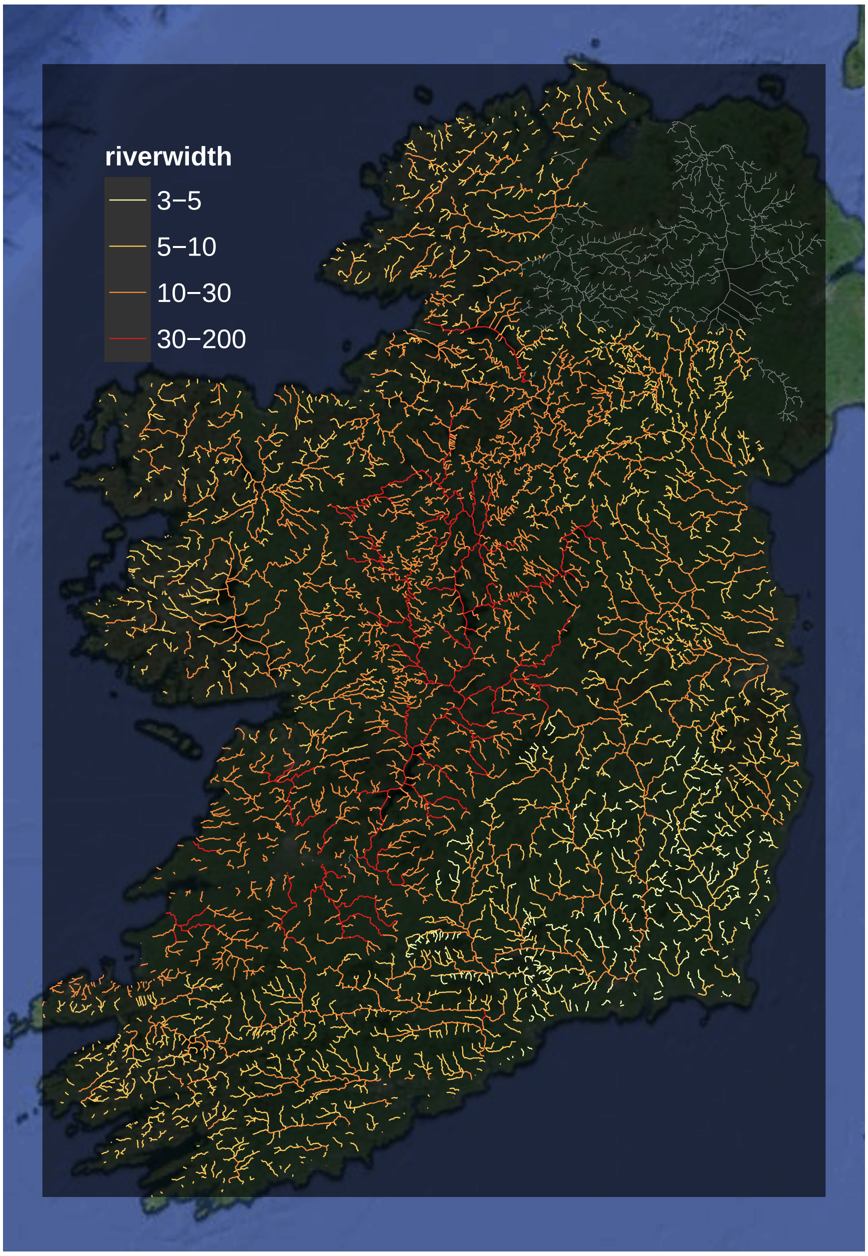


Figure 4.1: River width (m) predicted for Ireland using equation 3.1.

4.4.2 Ensuring that electrofishing surveys have a national coverage

Electrofishing data included in this analysis came from a variety of different sources 2.1. Apart from the surveys carried out as part of the WFD program (Figure 3.1), the surveys have a patchy distribution around the country. While we were conscious of this fact, we chose to include as many surveys as possible in order to obtain a national coverage, even though, in some cases, the primary objective of the surveys was not to estimate eel density. What this means however, is the variable year may be correlated with certain patches of data. The only way around this is to ensure that eel surveys are representative of the country as a whole. The results outlined in Annexe II give some confidence that the surveys were representative of the spatial variability found in Ireland, and continued expansion of the WFD program will ensure greater temporal coverage during the next round of monitoring.

4.4.3 Inclusion of lake productivity estimates

The estimates of lake production are central to the determination of total production of eel from Ireland. In this report, we use a fairly limited methodology, based on total production from only four catchments to extrapolate lake production for the whole country. This is not ideal. A better method of including lake production would be to use actual population estimates from a variety of lakes within each EMU to quantify eel production (numbers or biomass per hectare), and to build this into the EDA predictive modelling framework. This could be done in a very similar way as what is carried out with the fluvial production estimates. The current block in this line of research is a diffculty in converting standard lake eel quantification methods (e.g. fyke nets) to production. While we focus on lakes in this report, the same problem exists for large river segments and transitional waters. Future research in this area is essential to successfully implementing the Eel Regulation and ensuring the conservation of Eel stocks across Europe.

4.4.4 Conclusions on improving EDA

The following elements are listed as a roadmap for improving the accuracy of EDA

as applied to Irish eel stocks :

- Applying the modelling framework using the OS GIS coverage rather then the CCM coverage
- Developing a method of including lake production in a satisfactory way. This is not a problem restricted to Ireland - many member states have highlighted the fact that the quantification of eel in large water bodies (lakes, large river segments and transitional waters) is an issue, and this is an area that requires concerted action in the coming years.
- Including more electrofishing data into the analyses as they become available -primarily from the WFD monitoring programs and the national eel monitoring programs currently carried out by IFI

4.5 Overall Conclusions

The application of EDA to Irish Eel stocks has been a successful collaboration between researchers in Ireland and France. It has taken several years to carry out, as none of the co-authors were fully employed on the project. Nevertheless, it has proved to be a valuable exercise, with several positive outcomes:

- The EDA model produced biomass estimates which are in line with those previously calculated using the Irish model, giving confidence that the two methods are successfuly estimating total eel production for the country
- Much of the tedious, time consuming part of the EDA analysis has now been done, and will not have to be replicated again for any future runs in the coming years. All the code and databases used for the analysis are set up, and just need to be populated with new data as it becomes available
- Both Irish and French coauthors have benefited considerably from the exchange by integrating working methods and exchanging methods.
- A suite of recommendations are made for the improvement of EDA assessments of Irish eel stocks in the future

Acknowledgments

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Glossary

Akaike Information Criterion L'Akaike Information Criterion (1973) citeria allowing for the selection of the best model . 19

B_0 Pristine biomass, spawner escapement biomass in absence of any anthro-pogenic impacts. 21, 54

B_{best} Spawner escapement biomass corresponding to recent natural recruitment that would have survived if there was only natural mortality and no stocking. 21, 54

$B_{current}$ Spawner escapement biomass corresponding to the assessment year. For EDA this corresponds to the potential escapement biomass ($B_{potential}$) reduced from anthropogenic mortalities (silver eel fisheries and turbines mortality) dur-ing the downstream migration. 19, 53, 54

$B_{potential}$ Stock of silver eels (in biomass) before downstream migration, resulting from the modelling of eel densities in the river. 19

CCM Catchment Characterization and Modelling: Dataset with CCM2.1 information and all variables used for modelisation developped by the EU research center in Ispra. Each river segment corresponds to a small area, which is surrounded by the smallest catchment unit of the CCM2.1. The CCM has a simple topology, and EDA integrates some functions to calculate any river basin up-stream from one segment. 3, 7, 9, 17, 18, 23, 26, 29, 42, 66

EMU Eel Management Unit; administrative unit for eel management which in europe corresponds mostly to rivers basin districts, but can correspond to a coun-try as a whole (for instance in the Netherlands). "Member States shall identify and define the individual river basins lying within their national territory that constitute natural habitats for the European eel (eel river basins) which may in-clude maritime waters. If appropriate justification is provided, a Member State may designate the whole of its national territory or an existing regional admin-istrative unit as one eel river basin. In defining eel river basins, Member States shall have the maximum possible regard for the administrative arrangements re-ferred to in Article 3 of Directive 2000/60/EC [i.e. River Basin Districts of the Water Framework Directive]." EC No. 1100/2007. 7, 9, 16, 20, 21, 29, 42

ERS Electrofished river segments: Dataset with electrofishing information and all variables used for the model. The ERS unit is based on a geo-localized river network data base CCM v2.1. Each riversegment corresponds to a small aera, which is surrounded by the smallest catchment unit of the CCM2.1. 3, 17, 18, 23, 26, 29, 66

glass eel Young, unpigmented eel, recruiting from the sea into continental wa-ters. 16

silver eel Migratory phase following the yellow eel phase. Eel characterized by darkened back, silvery belly with a clearly contrasting black lateral line, enlarged eyes. Downstream migration towards the sea, and subsequently westwards. This phase mainly occurs in the second half of calendar years, though some are ob-served throughout winter and following spring. 1, 9, 16, 19, 21, 42, 43

yellow eel The yellow eel corresponds to the growing phase, that starts at the end of the glass eel metamorphosis when the pigmentation is complete. This stage performs most of the migration within the river system, within and be-tween rivers, and to and from coastal waters. It remains for some years in con-tinental water either in estuarine habitat or freshwater, before becoming a silver eel for the migration back to the Spawning ground. 1, 9, 16, 18, 19, 42–44

Part II

Annexes

Annexe 1

Table 6.1: Fluvial stock indicators in Ireland, $B_{current}$ is colour coded according to whether it is greater than (green) or less than (red) the biomass target set by the EU Regulation. ΣA is colour coded according to whether it is less than (green) or greater than (red) the mortality target equivalent to the biomass target (after (ICES, 2012) for ΣA). The amount of restocked eel is presented in glass eel equivalents, to standardize for eel ongrown before restocking. Note that the target for ΣA is lower than 0.92 if $B_{current} < 0.4B_0$.

		Biomass (t)			Mortality			Restocked (t)
	year	B0	Bcurrent	Bbest	Σ F	Σ H	Σ A	g.e. Equ.
NorW								
	2002	13.6	5.0	5.9	0.12	0.04	0.16	0
	2003	13.6	3.8	4.0	0.00	0.04	0.04	0
	2004	13.6	5.1	5.8	0.09	0.04	0.13	0
	2005	13.6	4.2	4.9	0.12	0.04	0.16	0
	2006	13.6	2.8	4.3	0.37	0.03	0.41	0
	2007	13.6	2.2	3.1	0.31	0.03	0.35	0
	2008	13.6	1.7	2.8	0.44	0.03	0.48	0
	2009	13.6	1.6	1.7	0.00	0.02	0.02	0
	2010	13.6	1.8	1.8	0.00	0.00	0.00	0
	2011	13.6	2.9	2.9	0.00	0.01	0.01	0
West								
	2002	13.2	10.1	11.7	0.15	0.00	0.15	0
	2003	13.2	7.2	9.1	0.24	0.00	0.24	0
	2004	13.2	9.6	11.8	0.20	0.00	0.20	0
	2005	13.2	8.0	9.8	0.20	0.00	0.20	0
	2006	13.2	4.3	6.8	0.46	0.00	0.46	0
	2007	13.2	3.6	5.5	0.44	0.00	0.44	0
	2008	13.2	2.6	4.1	0.46	0.00	0.46	0
	2009	13.2	3.4	3.4	0.00	0.00	0.00	0
	2010	13.2	3.7	3.7	0.00	0.00	0.00	0
	2011	13.2	5.5	5.5	0.00	0.00	0.00	0

Table 6.1: (continued)

		Biomass (t)			Mortality			Restocked (t)
	year	B0	Bcurrent	Bbest	Σ F	Σ H	Σ A	g.e. Equ.
Shan								
	2002	22.1	8.5	12.5	0.37	0.02	0.39	0
	2003	22.1	7.0	10.6	0.40	0.01	0.42	0
	2004	22.1	7.7	13.4	0.53	0.01	0.55	0
	2005	22.1	7.2	11.1	0.41	0.01	0.43	0
	2006	22.1	4.0	8.4	0.73	0.01	0.75	0
	2007	22.1	4.1	7.8	0.62	0.01	0.63	0
	2008	22.1	2.3	6.8	1.09	0.00	1.09	0
	2009	22.1	3.9	3.9	0.00	0.00	0.00	0
	2010	22.1	4.1	4.1	0.00	0.00	0.00	0
	2011	22.1	7.6	7.6	0.00	0.00	0.00	0

Table 6.1: (continued)

	year	Biomass (t) B0	Bcurrent	Bbest	Mortality Σ F	Σ H	Σ A	Restocked (t) g.e. Equ.
SouW								
	2002	7.1	9.1	9.5	0.02	0.02	0.04	0
	2003	7.1	6.6	6.7	0.00	0.02	0.02	0
	2004	7.1	8.8	9.0	0.00	0.02	0.02	0
	2005	7.1	7.3	7.5	0.00	0.02	0.02	0
	2006	7.1	4.8	5.0	0.02	0.02	0.04	0
	2007	7.1	3.8	3.9	0.00	0.02	0.02	0
	2008	7.1	2.6	2.9	0.11	0.02	0.13	0
	2009	7.1	2.7	2.8	0.00	0.02	0.02	0
	2010	7.1	3.0	3.1	0.00	0.02	0.02	0
	2011	7.1	4.5	4.5	0.00	0.01	0.01	0
SouE								
	2002	14.2	13.8	23.5	0.54	0.00	0.54	0
	2003	14.2	11.3	18.4	0.49	0.00	0.49	0
	2004	14.2	15.8	21.2	0.30	0.00	0.30	0
	2005	14.2	13.4	17.0	0.24	0.00	0.24	0
	2006	14.2	9.1	11.9	0.27	0.00	0.27	0
	2007	14.2	8.1	10.7	0.28	0.00	0.28	0
	2008	14.2	5.5	8.0	0.37	0.00	0.37	0
	2009	14.2	5.5	5.5	0.00	0.00	0.00	0
	2010	14.2	5.8	5.8	0.00	0.00	0.00	0
	2011	14.2	10.5	10.5	0.00	0.00	0.00	0
East								
	2002	6.4	2.3	4.3	0.61	0.01	0.62	0
	2003	6.4	1.6	3.4	0.72	0.00	0.73	0
	2004	6.4	2.6	4.0	0.43	0.00	0.44	0
	2005	6.4	2.5	2.8	0.10	0.01	0.10	0
	2006	6.4	1.7	2.0	0.12	0.01	0.13	0
	2007	6.4	1.5	1.7	0.16	0.00	0.17	0
	2008	6.4	1.1	1.8	0.51	0.00	0.51	0
	2009	6.4	1.0	1.0	0.00	0.01	0.01	0
	2010	6.4	1.1	1.1	0.00	0.01	0.01	0
	2011	6.4	1.9	1.9	0.00	0.00	0.00	0

Annexe 2

Homogeneity between ERS and CCM variables

Table 6.2: Comparison of the percentage of wetted area per discrete class created for the tested variable, for two datasets : the ers and the ccm

	Class(j)	CCM $\sum(S_j)/\sum(S)$	ERS$\sum(S_j)/\sum(S)$
cl_distance_sea p= 0.881			
	]0-11.2]	14.0	13.2
	]100.7-142.9]	15.0	12.5
	]11.3-35.9]	18.1	22.2
	]143-296]	21.7	16.3
	]36-68.7]	17.6	20.4
	]68.7-100.7]	13.5	15.4
cl_distance_source p= 0.184			
	]0-0.4]	1.7	0.1
	]0.4-1.2]	6.2	1.2
	]1.2-3]	13.4	7.6
	]23.4-300.5]	37.9	47.7
	]3-9.4]	19.6	20.4
	]9.4-23.4]	21.2	23.0
cl_elev_mean p= 0.908			
	]0.1-49.6]	24.5	18.3
	]117.2-186.6]	12.1	13.9
	]186.8-743.1]	7.8	7.9
	]49.7-68.5]	21.9	20.4
	]68.6-86.5]	17.9	19.9
	]86.6-117.1]	15.9	19.5
cl_slope_mean p= 0.959			
	]0-1.8]	26.5	25.4
	]1.9-2.8]	21.2	17.1
	]2.9-4.2]	16.6	16.3
	]4.3-6]	14.9	16.1
	]6.1-9.7]	12.8	16.7
	]9.8-59.5]	8.1	8.4

Table 6.2: (continued)

	Class(j)	CCM $\sum(S_j)/\sum(S)$	ERS$\sum(S_j)/\sum(S)$
cl_temp_mean p= 0.861			
	]0-8.4]	6.3	6.1
	]8.5-8.8]	15.2	15.1
	]8.9-9]	23.0	15.7
	]9.1-9.2]	18.2	20.5
	]9.3-9.6]	17.0	20.5
	]9.7-10.6]	20.4	22.1

Table 6.2: (continued)

	Class(j)	CCM $\sum(S_j)/\sum(S)$	ERS$\sum(S_j)/\sum(S)$
cl_rain_mean p= 0.64			
	]0-938.7]	17.5	20.7
	]1003.9-1060.2]	18.6	14.5
	]1060.3-1144.1]	17.2	21.1
	]1144.2-1267.5]	16.8	20.0
	]1267.6-1663.6]	10.9	12.2
	]938.8-1003.8]	19.1	11.5
cl_p_mod_calc_surf p= 0.162			
	]0-0.6]	25.6	38.1
	]0-0]	62.5	53.0
	]0.6-1]	11.9	8.9
cl_p_agricultural p= 0.494			
	]0-0.1]	23.9	30.5
	]0-0]	38.3	28.8
	]0.1-0.2]	22.1	22.0
	]0.2-1]	15.7	18.7

Annexe 3

Presence absence (Δ) model analysis

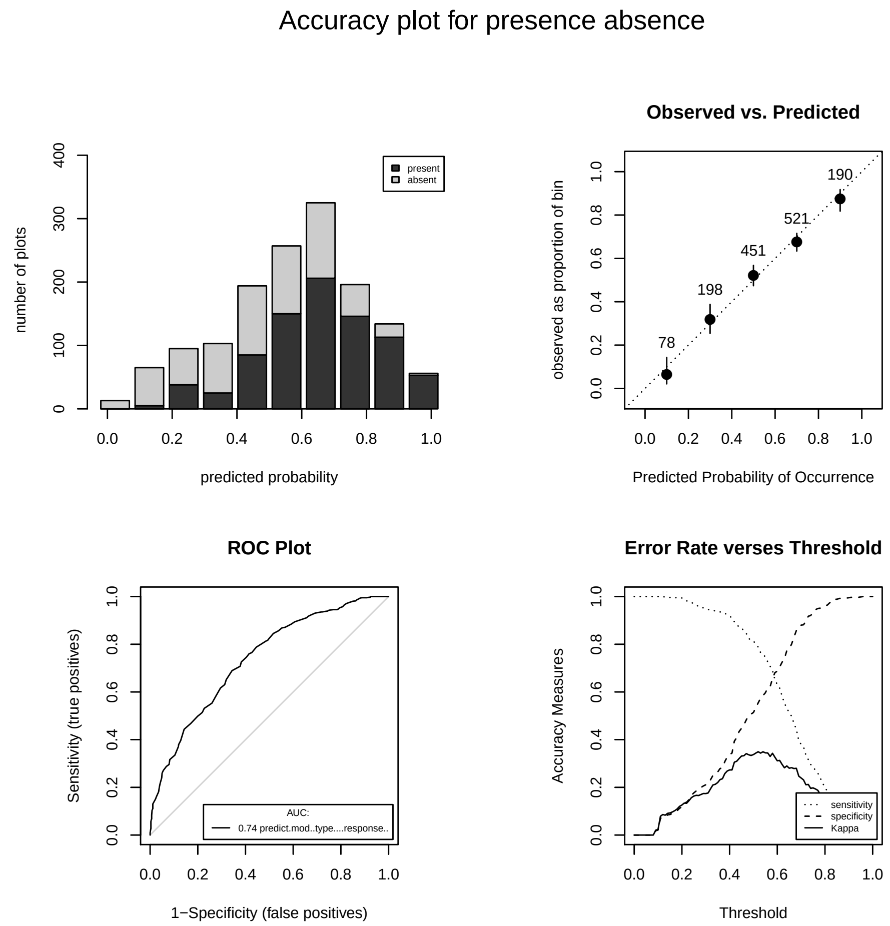

Figure 6.1: Model quality and threshold selection graphs for the presence-absence model (Δ) selected with a histogram plot (upper left), a calibration plot (upper right), a ROC plot with the associated Area Under the Curve (AUC) (lower left), and an error rate versus threshold plot (lower right).

Annexe 4

Density (Γ) model analysis

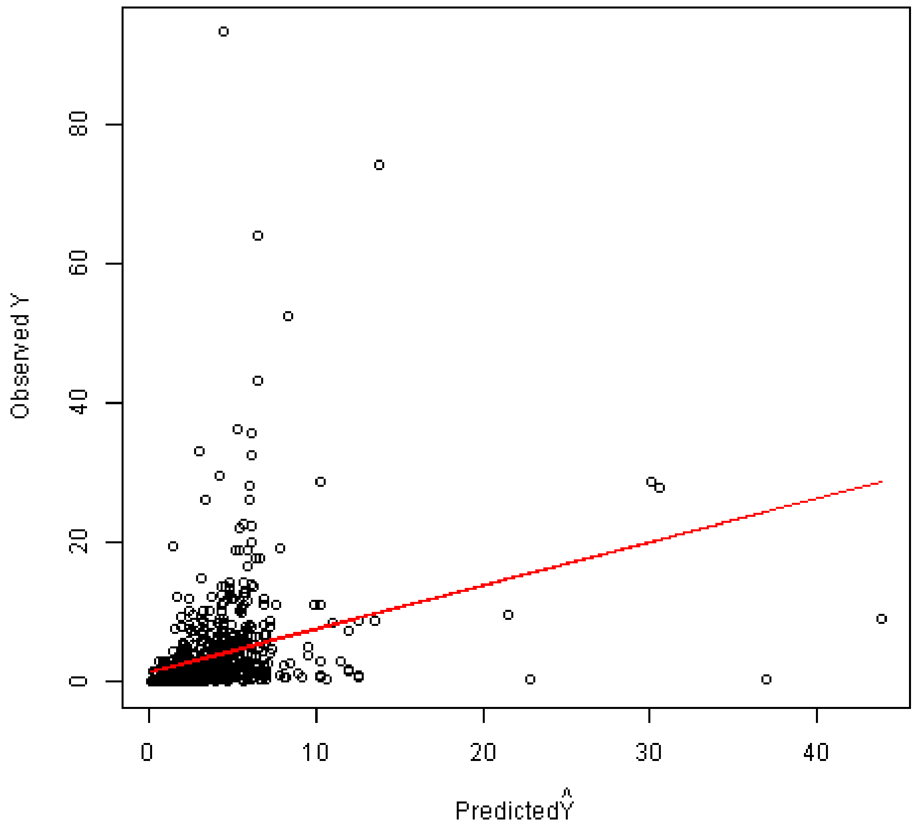

Figure 6.2: Fitted against predicted for the delta model.

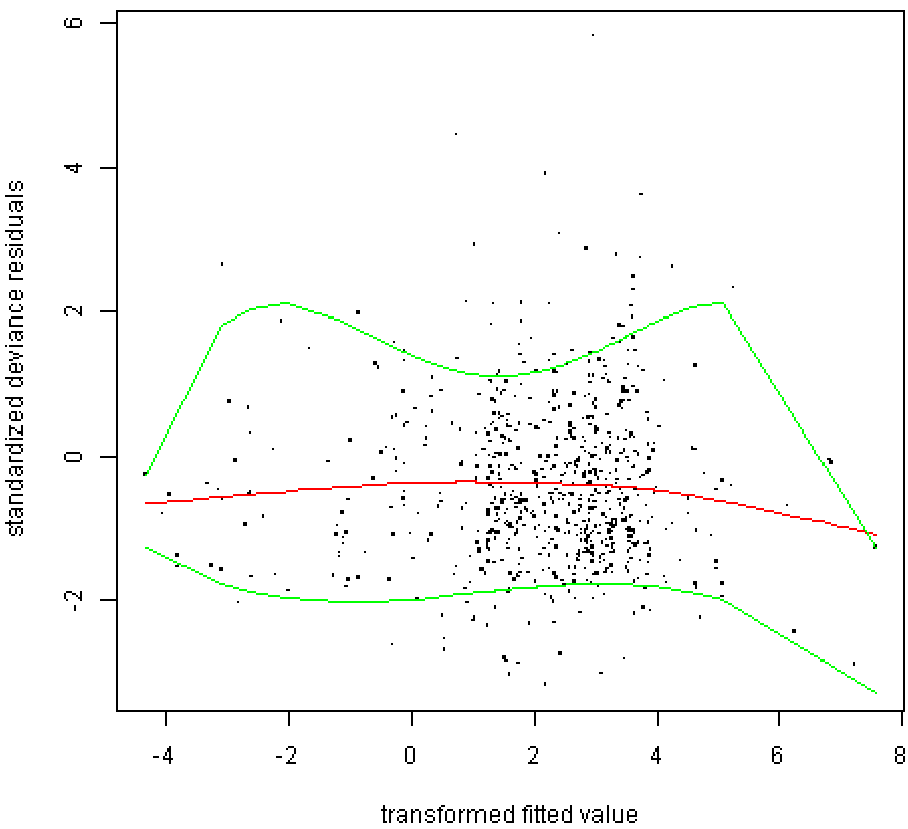

Figure 6.3: Standardized deviance residuals against fitted for the Γ model

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